Lauri Lindroos

Cognitive WLAN

Indoor Attenuation Analysis at UHF-band

Helsinki Metropolia University of Applied Sciences
Bachelor of Engineering
Information Technology
Bachelor's Thesis
15 June 2011

Preface

I would like to thank Nokia Corporation and Pekka Talmola in particular for this chance for an interesting and original study in the field of telecommunications. Additional thanks to Mikko Vääräkangas at Nokia Research Center and Kari Heiska at Digita for their help during the measurements.

Additionally, from Metropolia, I would like to thank Ville Jääskeläinen for guidance and technical instructions and Jonita Martelius for help with the layout and language. Their understanding and flexibility allowed me to finish the thesis during the summer.

Last but not least I would like to thank my dear friend Ville Karkiainen for the right kind of initial motivation to start my studies and additional doses along the way.

Helsinki, June 15, 2011

Lauri Lindroos

Abstract

Author(s) Title Number of Pages Date	Lauri Lindroos Cognitive WLAN - Indoor Attenuation Analysis at UHF-band 82 pages + 3 appendices 15 June 2011
Degree	Bachelor of Engineering
Degree Programme	Information Technology
Specialisation option	Telecommunications
Instructor(s)	Pekka Talmola, Lic. Tech. Ville Jääskeläinen, Principal Lecturer

Lack of free frequency ranges has caused a need to develop cognitive radios capable of using the already allocated spectrum ranges without interference to other radio transmissions. Temporary openings in already allocated spectrum are called white space.

This thesis was commissioned by Nokia Corporation to study relative indoor attenuation difference between a standard WLAN at 2,4 GHz and a cognitive radio WLAN at 618 MHz. Based on theory, the white space device WLAN should have had an advantage in lower attenuation due to lower frequency.

Test measurements indicated errors in the calibration of the white space device signal strength measurement software. The main attenuation measurements were conducted at two locations with different characteristics, a steel and glass building and a brick constructed building. At the first location WLAN traffic caused heavy interference to the measured standard WLAN signal whereas at the second building the calibration error manifested itself more severely. The transmitters were set close to each other. At each measurement point a set of five measurements was carried out to eliminate the effects of multipath fading and other phenomena affecting indoor propagation.

Based on a reference measurement, relative attenuation values were calculated and compared. These values and the relative attenuation difference were plotted as coverage maps with Matlab. As estimation was needed to correct faulty data caused by the calibration error, plots for original and corrected data were provided.

Due to measurement software error in the white space device part of the measurements were compromised. This coupled with heavy WLAN interference at one of the measurement sites led to inconclusive conclusions in the attenuation comparison. However the contested WLAN environment proved the benefits of the cognitive radio aspect, with the white space device providing much better coverage and readings when compared with the standard WLAN.

Keywords	Cognitive radio, white space, attenuation, WLAN, UHF

Metropolia

Tiivistelmä

Tekijä(t) Otsikko Sivumäärä Aika	Lauri Lindroos Cognitive WLAN - Indoor Attenuation Analysis at UHF-band 82 sivua + 3 liitettä 15.6.2011
Tutkinto	Insinööri (AMK)
Koulutusohjelma	Tietotekniikan koulutusohjelma
Suuntautumisvaihtoehto	Tietoliikennetekniikka
Ohjaaja(t)	TkL Pekka Talmola Yliopettaja Ville Jääskeläinen

Vapaiden taajuusalueiden puute on saanut aikaan tarpeen kehittää kognitiiviradioita, joilla voi käyttää jo varattuja osia spektristä aiheuttamatta häiriötä muille radiolähetyksille. Väliaikaisia taajuusaukkoja varatussa spektrissä kutsutaan termillä white space.

Tämä insinöörityö tehtiin Nokian toimeksiannosta tarkoituksena tutkia suhteellista eroa sisätilavaimennuksessa perinteisen 2,4 GHz WLAN yhteyden ja 618 MHz kognitiiviradioyhteyden välillä. Teorian perusteella matalammalla taajuudella toimivan white space yhteyden olisi pitänyt saada etua pienemmän vaimennuksen muodossa.

Testimittauksissa havaittiin virheitä white space laitteiston signaalitason voimakkuutta mittaavan ohjelman kalibroinnissa. Päämittaukset suoritettiin kahdessa erityyppisessä mittauskohteessa, lasista ja teräksestä rakennetussa sekä tiilistä rakennetussa rakennuksessa. Ensimmäisessä rakennuksessa WLAn liikenne aiheutti suurta häiriötä mitattavalle WLAN-signaalille. Toisessa rakennuksessa kalibrointivirheen vaikutukset olivat merkittävät. Lähettimet sijoitettiin lähekkäin toisiaan. Jokaisessa mittauspisteessä suoritettiin viisi erillistä mittausta monitievaimenemisen ja muiden sisätilaetenemiseen vaikuttavien ilmiöiden vaikutusten eliminoimiseksi.

Referenssimittauksen perusteella laskettiin vertailtavat suhteelliset vaimenemisarvot. Näiden arvojen ja suhteellisen vaimennuseron perusteella luotiin peittokartat Matlabilla. Kalibrointivirheen aiheuttaman tuloksien vääristymän korjaamiseksi tehtyjen arviointien vuoksi sekä alkuperäisillä että korjatuilla tuloksilla luotiin omat peittokarttansa.

Mittausohjelmistovirheestä johtuen osa mittaustuloksista oli epäluotettavia. Tämä ohjelmistovirhe ja toisessa mittauskohteessa koettu voimakas WLAN häiriö saivat aikaan vaimennusvertailun tuloksien rajallisen luotettavuuden. Raskaasti liikennöity WLAN-ympäristö kuitenkin todisti kognitiiviradion edut, sillä white space yhteys takasi merkittävässä määrin paremman kattavuuden sekä mittausarvot verrattaessa normaaliin WLAN-yhteyteen.

Avainsanat	Kognitiiviradio, taajuusaukko, vaimeneminen, WLAN, UHF

Contents

List of Figures

Abbreviations and Acronyms

1 Introduction 1

2 Theory 4

2.1 Transmission, Propagation and Reception 4
2.1.1 Antennas 4
2.1.2 Modulation 6
2.1.3 Interference 10
2.1.4 Free Space Path Loss 11
2.1.5 Noise 13
2.2 Indoor Propagation Challenges 15
2.2.1 Indoor Propagation 15
2.2.2 Fading 16
2.2.3 Multi-wall Model (MWM) 17
2.3 Decibels 18
2.4 Cognitive Radio 19
2.4.1 Definition 19
2.4.2 Spectrum Use 20
2.4.3 Cognitive Cycle 21
2.4.4 Spectrum Mobility 25
2.4.5 Spectrum Sharing 25
2.5 Television White Space 27

3 Setup and testing 30

3.1 Setup 30
3.1.1 Hardware 31
3.1.2 Software 34
3.2 Wired Tests 37
3.3 Wireless Test 42

4 Measurements 44

4.1 Nokia Research Center 44
4.1.1 Fourth Floor 45
4.1.2 Third Floor 49
4.1.3 Second Floor 51
4.1.4 First floor 54
4.2 Digita 57
4.2.1 Sixth Floor 58
4.2.2 Fifth Floor 65
4.2.3 Third Floor 72

5 Discussions and Conclusions 78

References 81

Appendices
Appendix 1. Test Results
Appendix 2. Measurement Results - Nokia Research Center
Appendix 3. Measurement Results - Digita

List of Figures

Figure 1. Amplitude modulation.
Figure 2. Frequency modulation.
Figure 3. Phase modulation.
Figure 4. Binary and quadrature phase shift keying.
Figure 5. Constellation diagrams of 8-PSK and 16-QAM.
Figure 6. Constructive and destructive interference.
Figure 7. Spreading of signal power.
Figure 8. Effect of noise on a signal and received data.
Figure 9. Indoor propagation challenges.
Figure 10. Decibels.
Figure 11. Dynamic spectrum access and spectrum holes.
Figure 12. Cognitive cycle.
Figure 13. Interference temperature.
Figure 14. Terrestrial TV transmission network coverage in Finland.
Figure 15. TV White space network structure and necessary components.
Figure 16. White space device.
Figure 17. DHCP router and US standard power strip.
Figure 18. Laptop with a mobile spoke.
Figure 19. TVBD Element Manager RF tab.
Figure 20. TVBD Element Manager White Space tab.
Figure 21. Homedale::WLAN Monitor access points tab.
Figure 22. Attenuators.
Figure 23. Wired pre-measurements.
Figure 24. Wired post-measurements.
Figure 25. White space device spectrum.
Figure 26. NRC 4th floor measurement points.
Figure 27. NRC 4th floor white space device relative attenuation.
Figure 28. NRC 4th floor WLAN relative attenuation.
Figure 29. NRC 4th floor relative attenuation difference.
Figure 30. NRC 3rd floor measurement points.
Figure 31. NRC 3rd floor white space device relative attenuation.

Figure 32. NRC 3rd floor WLAN relative attenuation.
Figure 33. NRC 3rd floor relative attenuation difference.
Figure 34. NRC 2nd floor measurement points.
Figure 35. NRC 2nd floor white space device relative attenuation.
Figure 36. NRC 2nd floor WLAN relative attenuation.
Figure 37. NRC 2nd floor relative attenuation difference.
Figure 38. NRC 1st floor measurement points.
Figure 39. NRC 1st floor white space device relative attenuation.
Figure 40. NRC 1st floor WLAN relative attenuation.
Figure 41. NRC 1st floor relative attenuation difference.
Figure 42. Digita offices 6th floor measurement points.
Figure 43. Digita offices 6th floor white space device relative attenuation.
Figure 44. Digita offices 6th floor white space device relative attenuation, modified.
Figure 45. Digita offices 6th floor WLAN relative attenuation.
Figure 46. Digita offices 6th floor relative attenuation difference.
Figure 47. Digita offices 6th floor relative attenuation difference, modified.
Figure 48. Digita offices 6th floor WSD downlink throughput.
Figure 49. Digita offices 6th floor WSD uplink throughput.
Figure 50. Digita offices 5th floor measurement points.
Figure 51. Digita offices 5th floor white space device relative attenuation.
Figure 52. Digita offices 5th floor white space device relative attenuation, modified.
Figure 53. Digita offices 5th floor WLAN relative attenuation.
Figure 54. Digita offices 5th floor relative attenuation difference.
Figure 55. Digita offices 5th floor relative attenuation difference, modified.
Figure 56. Digita offices 5th floor WSD downlink throughput.
Figure 57. Digita offices 5th floor WSD uplink throughput.
Figure 58. Digita offices 3rd floor measurement points.
Figure 59. Digita offices 3rd floor white space device relative attenuation.
Figure 60. Digita offices 3rd floor WLAN relative attenuation.
Figure 61. Digita offices 3rd floor relative attenuation difference.
Figure 62. Digita offices 3rd floor WSD downlink throughput.
Figure 63. Digita offices 3rd floor WSD uplink throughput.

Abbreviations and Acronyms

AC	Alternating Current
AM	Amplitude Modulation
BNC	Bayonet Neill-Concelman
BPSK	Binary Phase Shift Keying
DC	Direct Current
DHCP	Dynamic Host Configuration Protocol
EIRP	Equivalent Isotropic Radiated Power
EM	Electromagnetic
FCC	Federal Communications Commission
FM	Frequency Modulation
FSK	Frequency Shift Keying
FSPL	Free Space Path Loss
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITU	International Telecommunication Union
LED	Light Emitting Diode
MWM	Multi-wall Model
NRC	Nokia Research Center
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
TV	Television
TVBD	Television Band Device
TVBDEM	Television Band Device Element Manager
UHF	Ultra High Frequency
WLAN	Wireless Local Area Network
WS	White Space
WSD	White Space Device

1 Introduction

The viable frequency ranges for wireless telecommunication have already been allocated to various services. As new allocations are not available and some of the currently used frequency ranges are not used as efficiently as possible, a new approach to providing connectivity to users is needed. This offers an opportunity to utilize a concept called cognitive radio. The Radiocommunication Sector of the International Telecommunication Union defines cognitive radio as follows:

> A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained. [1:9]

Cognitive radio is usually an application on a software defined radio. The main properties of a software defined radio can be defined by the software settings. These properties include frequency, bandwidth, modulation and network access. [2:4] These software defined abilities allow it to detect and use free radio frequencies to transmit and receive information while avoiding interference with other radio systems. [2:1]

White space (WS) is a hole or gap in the spectrum. [3:2130] There can be several reasons for these spectrum holes and in the case of television white space, two main reasons can be defined, one of the reasons being the channels freed up by transition to digital television. [4:6] and the other reason caused by the way terrestrial television broadcast networks are built. [5] The properties of terrestrial television broadcast networks are discussed further in the section containing the theory.

The purpose of this study was to determine whether television whitespace WLAN could be used as an alternative solution to the current WLAN standards. The aim was also to find out if and what advantages real-life application of TV WS WLAN could offer. The method was to observe received signal strength indicator (RSSI) of the white space device and the WLAN adapter of the laptop. These values were recorded on an Excel sheet, an average RSSI value was calculated for both connection types and later plotted as coverage maps with Matlab.

As the white space technology is still young and the devices provided for the study were prototype devices only capable of limited bandwidth, the characteristics chosen for comparison were indoor propagation and relative attenuation.

Relatively low frequency channels used for television broadcasts (54 MHz to 698 MHz) offer an opportunity to utilize cognitive radio while benefiting from the suitable characteristics of this frequency range when compared to the usual wireless frequency of 2.4 GHz. [4:6] Theoretically longer ranges and better penetration of obstacles with same transmitting power should be achieved by using lower frequencies. [4:18]

This study was commissioned by Nokia Corporation in co-operation with Digita. The two companies had already experimented with long range outdoor use of television white space and felt that there was a need for practical experiments with white space use indoors as well. The equipment was provided by Nokia, who in turn had acquired it from Spectrum Bridge Inc.

The measurements were conducted in two different locations in the Helsinki metropolitan area. The locations were chosen due to the difference in building techniques of the premises. Nokia Research Center in Ruoholahti Helsinki is a modern building constructed mainly of glass and steel. The Digita offices in Pasila is a more traditional brick constructed office building. The Metropolia building in Hietalahti, an old building with thick stone walls dating back to the beginning of 20th century, was used for test measurements.

The measurements were conducted with a laptop installed with TVBD Element Manager to manage and track the television white space (TV WS) connection and Homedale WLAN Monitor to monitor the wireless network adapter on the laptop. A WLAN access point and television white space hub were then set up close to each other and TV WS spoke connected to the laptop. Measurements were done in sets of five for each connection, and when the connection permitted, also a speed test value was recorded. Measurement points were then marked on a map and the corresponding values were recorded on an Excel-worksheet.

This report is written in five main sections, the first being the introduction. The second section contains the theory and background information needed to understand the phenomenon being measured. The third section consists of an account of the software and hardware used in the measurements and the testing of the said equipment. Information gathered during the measurements is displayed and analyzed in the fourth section and the conclusions are drawn in the final section.

2 Theory

This section contains the theory and background information relevant to this thesis. First the basics of radio wave generation and propagation are examined. After this the terms cognitive radio and television white space are discussed in more detail.

2.1 Transmission, Propagation and Reception

Electromagnetic (EM) radiation is the means of transferring energy (information, data, light etc.) through a medium. [6:1102] The fundamentals of electromagnetic radiation will be discussed in this section. The focus will be on the propagation of the electromagnetic waves as it is essential for wireless communication. In general, electromagnetic radiation has properties which give it a dualistic nature: depending on the application, it can be interpreted as either waves or particles. The particle properties are more apparent on a smaller scale, at the atomic level, and the wave properties on a larger scale and at longer distances. [6:687]

The basic unit of electromagnetic radiation is a photon. Photon is an elementary particle without any mass, and as an elementary particle it is governed by quantum mechanics. This gives it the dualistic nature of exhibiting both wave and particle properties at the same time. This dualistic nature causes several propagation related phenomena and challenges, which will be discussed in the next section. In this section, the devices necessary for transmission and reception, the antennas, will be discussed next.

2.1.1 Antennas

> Antennas transmit and receive radio waves. They operate as matching devices from a transmission line to the free space and vice versa. [7:205]

As the description states, power is fed to an antenna, the antenna then radiates the EM field into the surrounding medium. Antennas need to have proper construction and material to be able to match the free space with the transmission line with as little loss and reflections as possible. [7:205]

A dipole antenna is a simple and important type of antenna. It consists of a straight wire usually split in the middle to provide connection to the transmission line feeding the power. [7:217] When the length of the antenna is half of the wavelength of the signal to be radiated, the maximum strength of the radiation is on a plane perpendicular to the antenna and additionally no radiation is emitted in the direction of the antenna. [7:218] This makes half-wave dipole the most important of dipole antennas.

Two key concepts of an antenna are its effective area and antenna gain, which are now discussed.

An **isotropic antenna** is a theoretical model of an ideal antenna. It has no surface area and it radiates the electromagnetic radiation to all directions in an equal amount. [7:208]

The **effective area** of an antenna is defined by how well an antenna can receive power from incoming electromagnetic radiation. It can be thought of as an area through which all radiation is picked up and utilized by the receiving antenna. Since transmitting and receiving are reciprocal, the effective area is the same in both directions. The effective area for an isotropic antenna can be defined as

$$\frac{\lambda^2}{4 * \pi},$$

where λ is the wavelength of the signal. [7:210]

The effective area of a directional antenna is then defined as

$$\frac{G * \lambda^2}{4 * \pi},$$

where λ is the wavelength of the radiation and G the gain of the antenna.[7:210]

The antenna **gain**, mentioned above, is defined by how much radiation they can direct in a certain direction. Since total signal power stays the same, this means less power is transmitted in other directions. Antennas cannot amplify the signal they transmit or receive since they have no outside power source. Antenna gain is a measure of how much higher the signal power is at a given location/distance compared to the case where the transmitting antenna would be an isotropic antenna.[7:210] The unit of this measure is dBi which stands for decibels over isotropic. The antenna gain is reciprocal, meaning the radiation direction is irrelevant. [7:205]

To be able to transmit data on radio waves, a carrier wave must first be modulated with the digital data converting the data streams into radio waves with desired properties. Next section discusses various ways of modulating the signal.

2.1.2 Modulation

Depending on the modulation technique, the modulated symbol can consist of variable number of bits. A symbol is defined as a certain amplitude, phase and frequency of the signal. [8:146] Depending on the used modulation method a high frequency carrier waveform is then modulated accordingly to be used to transfer the information.

Carrier modulation is important to any given wireless communication technology. In carrier modulation a relatively low frequency signal containing the information is modulated with a high frequency carrier. This is done to be able to transfer the spectrum, frequency components, to a higher frequency band. [8:129] Figure 1 displays the carrier modulation of a signal using basic **amplitude modulation (AM)** as an example.

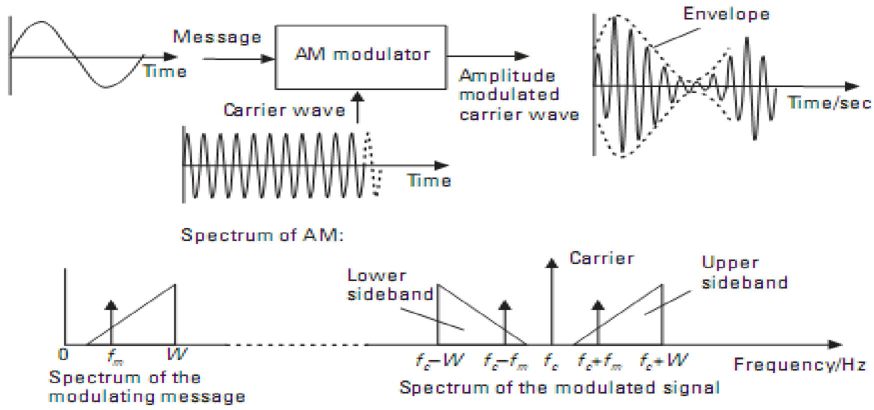

Figure 1. Amplitude modulation. [8:130]

As can be seen in the figure, carrier modulation, in this case amplitude modulation, "lifts" the information signal to the higher frequency of the carrier. The envelope in the figure is the original form (amplitude) of the information signal, which can then be detected at the receiver by demodulating. A drawback of carrier modulation is the doubled need for bandwidth due to the original spectrum being mirrored using the carrier as an axis. Even if the example here is of amplitude modulation this bandwidth need is valid for all carrier modulation methods. [8:131]

Frequency modulation (FM) is a modulation method where the frequency of the carrier is changed according to the message while the amplitude remains constant. [8:134] Figure 2 shows the principle behind linear FM.

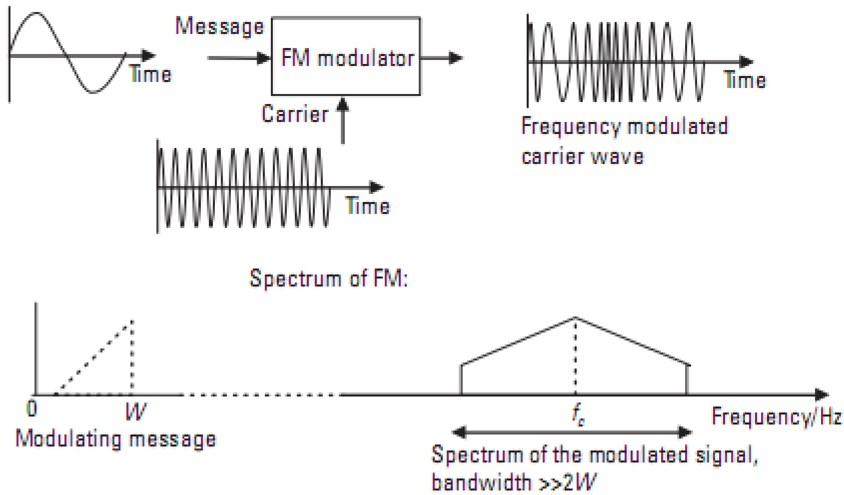

Figure 2. Frequency modulation. [8:134]

The figure shows how the frequency of the carrier is increased as the value of the message increases and vice versa. In FM the change to the modulating signal is linear but a modification to this modulation technique called **frequency shift keying** (FSK) assigns certain frequencies to certain symbols of the message. Basically several carriers with different frequencies are used for modulation. [8:135]

Benefits of FM and FSK manifest themselves in the detection of the signal. Since the frequencies denoting the different symbols are easily distinguished from one another, only instances where the received signal crosses zero voltage are necessary to be detected. Furthermore, since the amplitude of the transmitted signal is kept constant any effects of disturbances to the signal, which mainly affect the amplitude, are minimized as the lateral change of even relatively large amplitude changes is rather small. [8:134]

Phase shift keying (PSK) is a modulation scheme of which there are several variations. In Figure 3 the general principle behind all these variations is displayed.

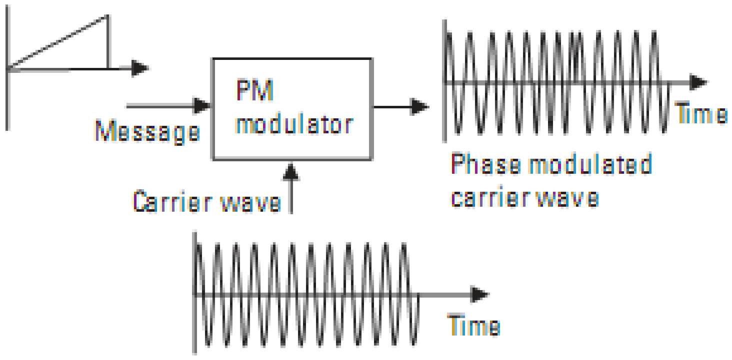

Figure 3. Phase modulation. [8:135]

As the state of the information signal changes, the phase of the signal is reversed, as can be seen from the resulting phase modulated carrier wave. After the midpoint the curve does not dip under the axis as it normally would. Instead from that point on it is mirrored around the axis. [8:135]

This can also be seen in Figure 4 in which is included the information value, zeros and ones, of the signal at a given state. Which state corresponds to a one or a zero is a matter of definition. This modulation method is called binary PSK as it has two states. A higher modulation called quadrature PSK having four states is also included in Figure 4.

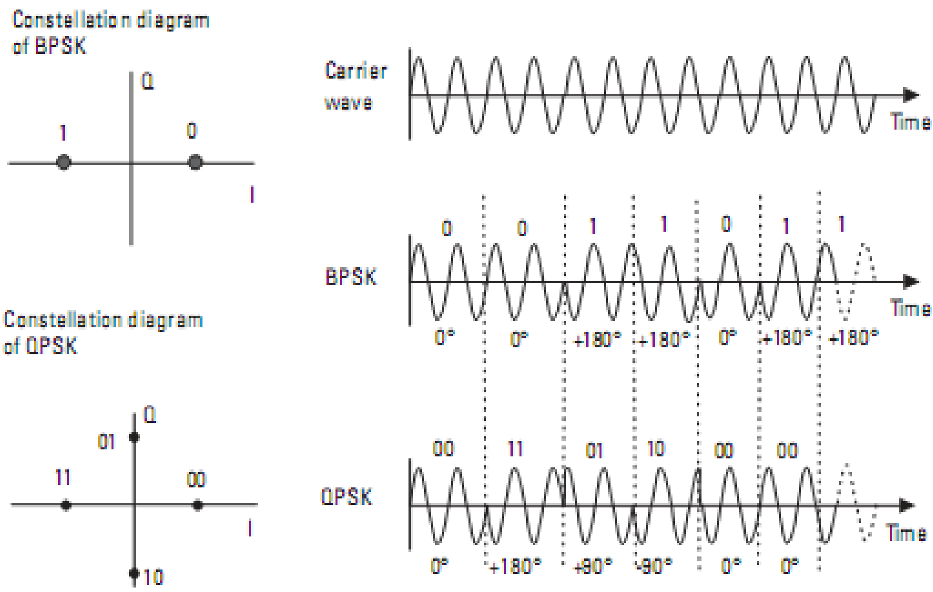

Figure 4. Binary and quadrature phase shift keying. [8:136]

In all PSK techniques the amplitude of the signal remains constant, only the amount by which the phase changes is different. As the full circle of the constellation diagram corresponds to a phase shift of 360 degrees, in BPSK the difference of states is 180 degrees and in QPSK 90 degrees. The higher the modulation, the smaller the difference, and higher the possibility of an error at the reception as the noise and other interference distort the signal. However QPSK also gives more benefit than BPSK as the bit rate of the transmission is doubled, one symbol being able to carry two bits of information. [8:137]

To gain further improvement in the bit rate more bits are multiplexed into one symbol. The number in front of the acronym of the modulation tells the number of states the signal can have. It is always a power of two, the power signifying the number of bits in the symbol. 8-PSK has eight states separated by 45 degree phase difference. This method is rather sensitive to noise due to small tolerance for an error that a method combining phase and amplitude modulation has been developed. This method gives more possibilities to distinguish states of the signal from one another and is called **quadrature amplitude modulation** (QAM). [8:137] The constellation diagrams for 8-PSK and 16-QAM are displayed in Figure 5.

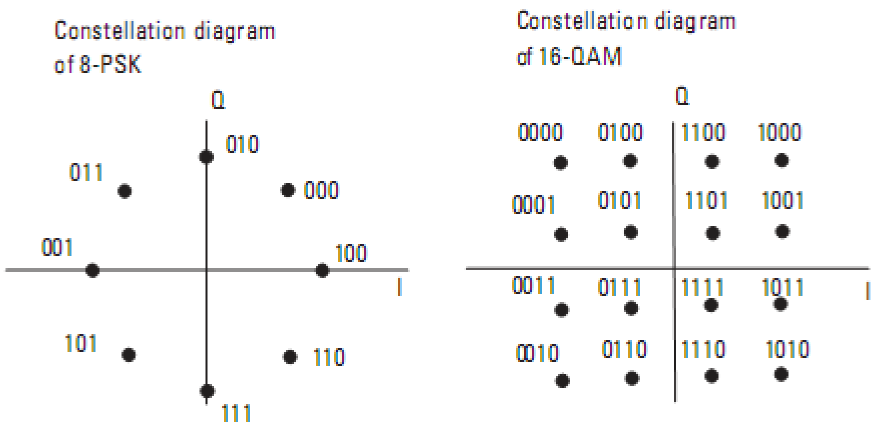

Figure 5. Constellation diagrams of 8-PSK and 16-QAM. [8:137]

8-PSK works as the lower order PSK variants. 16-QAM signal on the other hand has possibility for twelve different phases and three different amplitudes. This gives the signal 16 different possibilities for a state resulting in four bits per symbol. Even higher variants of QAM are used when the noise rate of the channel permit. [8:138] Should the interference increase the modulation level can be lowered to allow more error tolerance, and vice versa. [8:137]

Antennas are needed to transmit and receive signals, and modulation is necessary to enhance the efficiency of transmissions. As a signal travels (propagates) through a medium, it experiences several phenomena that affect it: The strength of the signal fades as it travels, it may encounter other signals or obstacles. Following sections focus on discussing the phenomena that affect a signal between transmission and reception.

2.1.3 Interference

Interference takes place when multiple waves are added (super positioned) together forming a new waveform. Depending on the phase difference of the wave's interference can be either constructive (in-phase) or destructive (out of phase). [6:647] Figure 6 illustrates the two types of interference.

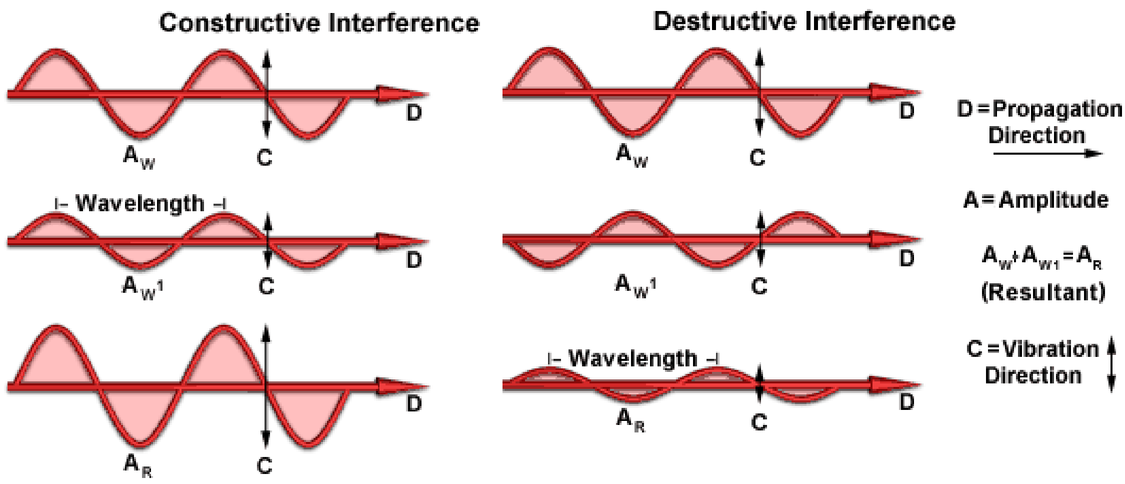

Figure 6. Constructive and destructive interference. [9]

In both types of interference the amplitudes of the interfering waves are added together at every point of the wave. In Constructive interference, due to the waves being in-phase the added amplitudes are on the same side of the axis defined by the propagation direction and the resulting amplitude A_R is larger. In destructive interference the amplitudes are on the opposite sides of the axis and thus they are countering each other's effect resulting in smaller amplitude. The interfering signals can naturally be of any form and interfere at any phase difference.

2.1.4 Free Space Path Loss

Free space path loss (FSPL) is the loss in power caused by the spreading of electromagnetic radiation in the medium. The transmitted power from isotropic antennas is distributed over a spherical surface and the radiated power per unit area decreases in proportion to the square of the radius because the area of the spherical surface increases in proportion to the square of the radius. [8:141]

To understand how the free space path loss is determined, two separate phenomena need to be combined. Firstly the spreading of electromagnetic radiation in free space can be seen as an expanding surface of a ball. Thus the power transmitted at any given moment spreads evenly on the surface of the ball. The intensity of the signal at certain point at certain distance from the source can be calculated by dividing the source signal strength by the surface area of the ball, where the radius of the ball is this distance, [8:141] as Figure 7 illustrates.

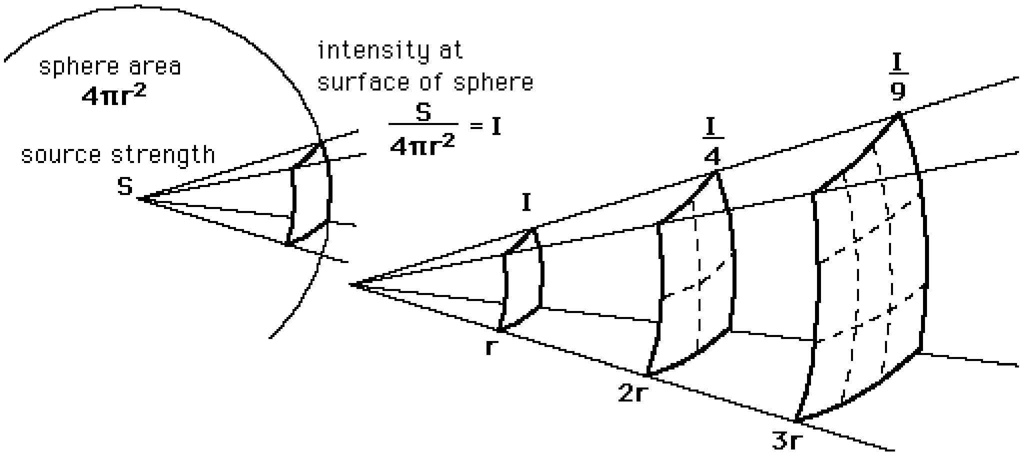

Figure 7. Spreading of signal power. [10]

And the formula for this intensity is

$$I = \frac{S}{4 * \pi * r^2},$$

where S is the source signal strength and d the distance from the source. [6:621] [8:142]

Second issue to take into account is effective area of the antenna, which was earlier explained. For isotropic antenna the received power is defined by the following formula:

$$P = I * \frac{\lambda^2}{4 * \pi} = \frac{S * \lambda^2}{(4 * \pi * r)^2},$$

where I is the intensity of the radiation at the distance the isotropic antenna is from the radiation source and λ is the wavelength of the radiation.

The loss given by the ratio of transmitted power over the received power is called the free space path loss:

$$FSPL = \left(\frac{4 * \pi * r}{\lambda} \right)^2 = \left(\frac{4 * \pi * r * f}{c} \right)^2$$

In this equation *r* is the distance from the transmitter, *λ* the wavelength and *f* the frequency of the signal and *c* the speed of light. [8:142] The latter form of the equation is gotten by substituting wavelength according to the following equation:

$$v = \lambda * f$$

In this equation *v* is the speed of the EM wave, *λ* its wavelength and *f* its frequency. The speed of an EM wave depends on the medium in which it is travelling. In vacuum this speed is the speed of light. For other substances the speed is different but always lower than the speed of light. Basically for any given medium the speed is constant, so by setting either the frequency or wavelength we also set the other property. [6:609, 5:619]

Analysis of the FSPL formula shows that the loss at higher frequencies is higher than at lower frequencies and also longer distance means greater loss. As the variables in the equation are in power two it means that either doubling the frequency of the signal or the transmit distance would increase the loss by a factor of four.

2.1.5 Noise

As the signal power decreases during the propagation, the information transmitted by the signal becomes harder to interpret at the receiving end. In addition to the losses degrading the signal, another factor has to be taken into account. This factor is called *noise*, which is interference caused by the thermal movement of the particles. Thermal noise includes the background radiation of the universe and the noise caused by the transmitting and receiving devices themselves. In telecommunications the signal contains data which can be corrupted during transmission by noise. [8:148] In Figure 8 the effects of noise on a transmitted signal can be seen.

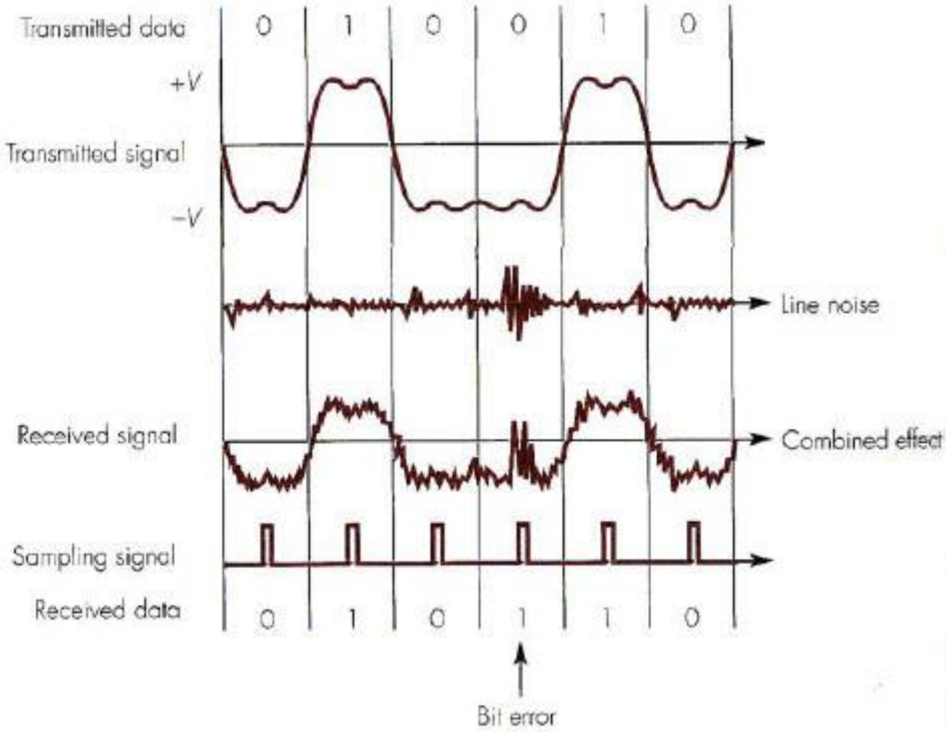

Figure 8. Effect of noise on a signal and received data. [11]

The transmitted data consists of zeros and ones, which are created by adjusting the voltage in the transmitter. In this instance positive voltage represents ones and negative zeros. The noise in the channel causes distortion in the received signal. At the receiver the signal is sampled at certain intervals and if noise distortion at the sampling instance is large enough, the result is a bit error in received data.

The ratio between the signal power and noise power is called signal-to-noise ratio. This ratio expresses the quality of the transmission. Since the signal power decreases during propagation, at some point the signal-to-noise ratio will decrease to a point where the data cannot be extracted from the signal. [8:148]

Noise is not the only challenge facing telecommunications. Next section discusses these challenges, especially from the indoor propagation point of view.

2.2 Indoor Propagation Challenges

The challenges discussed in this section hold true for outdoor propagation as well, however they compound in indoor environment where the line of sight path from transmitter to receiver is harder to achieve. Indoor environments are also generally more cluttered and moving objects, including humans, can cause significant interference.

2.2.1 Indoor Propagation

Figure 9 illustrates various challenges in indoor propagation. These challenges include reflection, scattering and diffraction.

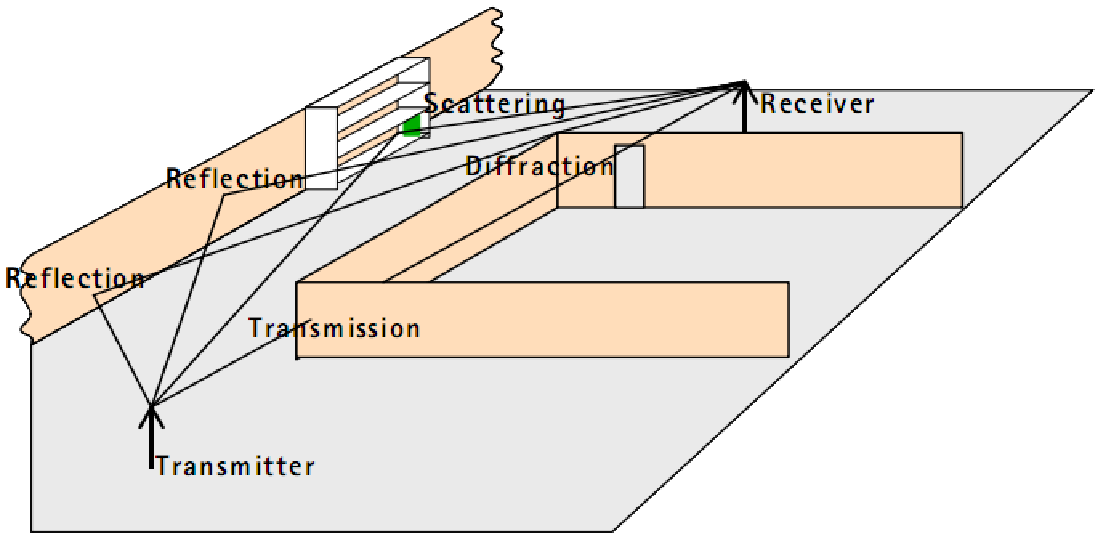

Figure 9. Indoor propagation challenges. [13:20]

Diffraction means the bending of the wave behind an obstacle. This is due to Huygens' principle, which states that every point on a wave front is also a source of a spherical wave. The wave front passing behind the corner in Figure 9 is then the tangent of these spherical waves. [6:681]

Fast changes in the medium through which the radiation is propagating cause scattering and reflections. [7:252] Scattering happens when radiation hits a small particle in relation to the wavelength of the radiation. [6:716] In scattering part of the coherent wave is transformed into incoherent form and radiates in a large angle. This weakens the signal. [7:263]

Reflection works in the same manner as diffraction, as the contact point of the wave on an obstacle is considered a source of another spherical wave, which then propagates in all directions. In the figure only the direction towards the receiver is noted. The amount of radiation reflected depends on the material, as does the amount of radiation that penetrates into the material.

2.2.2 Fading

As a result of reflected, diffracted, scattered and direct signals, the message arrives at the receiver multiple times. This is called multipath propagation. Multipath propagation causes small-scale fading in the signal. Small-scale fading means phase and amplitude changes caused by small changes (roughly a wavelength) of position in the interfering signals. Large-scale fading is caused by a prominent obstacle in the way of the signal. Due to the obstacle, the path loss increases rapidly in relation to the distance traveled. [7:261]

Fading can be further divided into frequency selective and flat fading. In frequency selective fading, the radio channel affects certain frequency components more than the others. When flat fading is concerned, all frequency components fade equally. Based on the speed of changes occurring in the transmission channel, the fading can also be categorized as fast or slow. [7:261] For example movement in the transmission channel causes fast fading. [14:179]

To attempt to predict the behavior of signals and estimate indoor WLAN coverage, various models have been developed. Next section focuses on one of these models, the multi-wall model.

2.2.3 Multi-wall Model (MWM)

The multi-wall model is not the most simple of the available models, but this also enables it to give more accurate predictions of loss in indoor environments.[14:176] The following equation gives the total loss predicted by MWM.

$$L = L_{FSPL} + L_C + \sum_{i=1}^{I} k_{wi} * L_{wi} + k_f^{\frac{k_f+2}{k_f+1} - b} * L_f$$

where symbols indicate the following:

L_{FSPL}	free space path loss
L_C	constant loss
L_{wi}	loss at wall of type i
L_f	loss between two floors
k_{wi}	number of penetrated walls of type i
k_f	number of penetrated floors
b	empirical parameter
I	number of wall types

Constant loss is normally close to zero, so in most cases it can be ignored. [14:177] As can be seen, wall types can be categorized separately to provide better accuracy. The empirical parameter *b* is used to characterize the observation how floor loss is a non-linear function of the number of penetrated floors. [14:176]

According to testing done at Technical Research Centre of Finland (VTT) and several other instances, coefficients for the equation have been determined for 1800 MHz and 900 MHz bands. [14:178] Two types of walls were considered in the testing: light walls not bearing load and heavy load-bearing walls. Light walls were considered to be plasterboard or particle board walls or concrete walls with less than 10 cm thickness. Concrete or brick walls thicker than 10 cm were considered heavy walls. [14:177] Table 1 shows the measured coefficients.

Table 1. Coefficients for multi-wall model on 1800 MHz and 900 MHz bands. [14:178]

Frequency	**Thin wall loss [dB]**	**Thick wall loss [dB]**	**Floor loss [dB]**	**b**
1800 MHz	3,4	6,9	18,3	0,46
900 MHz	1,9	3,4	18,3	0,46

In multi-wall model losses are calculated in decibels. The following section provides information about the unit and the calculation processes using it.

2.3 Decibels

The concept of decibel (dB) is important to understand in telecommunications. In addition to this the decibel milliwatt (dBm), an alternate unit to a watt when discussing power-related issues, needs to explained. Figure 10 displays the fundamentals of decibel calculations.

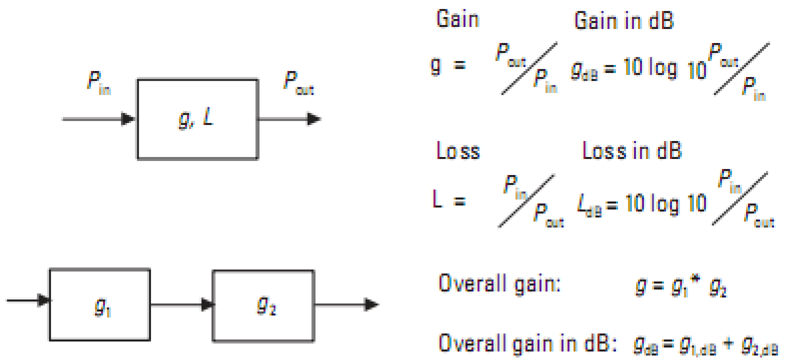

Figure 10. Decibels. [8:116]

As can be seen in Figure 10 above, to convert power level changes into decibels ten times ten base logarithm is taken of the output and input power ratio. If the ratio is exactly one, resulting change in decibels is zero. If the ratio is greater than one, change in dB is positive and if the ratio is less than one, the change in dB is negative. Two important ratios for reference are one half and two, which correspond respectively to changes of -3 dB and 3 dB.

Calculating in decibels simplifies the handling of large numbers, as a gain of 100000000 corresponds to the gain of 80 dB. Also calculations are relatively simple, as with decibels only addition and subtraction are needed. [8:116]

Changes in power levels are notified in decibels, but the absolute value of the power level itself needs a different definition. A decibel-based scale can be used here as well. The level of power is often expressed in decibel milliwatts (dBm). To get power in dBm the power level that is wanted to be converted is compared to the power of one milliwatt as follows:

$$P_{dBm} = 10 * \log_{10}(\frac{P}{1mW})$$

In calculations decibels and decibel milliwatts are easy to use as the dB can simply be added or subtracted from dBm values. The resulting value is always given in dBm. [8:117]

2.4 Cognitive Radio

The term cognitive radio was first defined by Joseph Mitola in 1998. [12:ix] He defined three different levels of intelligence in radio systems: aware, adaptive and cognitive radios.

2.4.1 Definition

Aware radios can be either radio frequency (RF) location aware or user location aware. RF location aware radios associate some aspect of RF to the location, for example the received signal strength indication (RSSI). User location aware radios associate some user behavior to a location, for example the space-time distribution of demand.

For a radio to be adaptive, it needs to take action: either to react to a change in the RF environment or predict a change based on known attributes. A good example is a cellular phone switching to lower data rate when the connection gets worse. This example also works with prediction, if the phone has information how the RSSI drops always in a certain location.[12:6]

The requirements for cognition are significantly higher. In addition to being aware and able to take action in the RF world, the device should perceive the user's needs, for example contacting emergency services if the user needs medical assistance. The device also should gather information, learn, instead of having to be preprogrammed with everything. [12:10] The learning process could take place by being told by a trusted source (other device) or by observations by the device itself. [12:11]

In addition to the definition based on intelligence level of the radio, two main characteristics of cognitive radio can be defined:

> **Cognitive capability** refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency band of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected. [3:2129]
>
> **Reconfigurability** enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design. [3:2129]

Cognitive radios then use these capabilities to sense and access RF spectrum and adapt to its changes. The process is called the dynamic spectrum access and is discussed in the following section.

2.4.2 Spectrum Use

In this thesis the focus is on the RF aspects of cognition, the main functions of which are:

- Spectrum sensing: Detecting unused spectrum and sharing it without harmful interference with other users.
- Spectrum management: Based on user's needs, using the best available spectrum.
- Spectrum mobility: Maintaining seamless connection while changing the location in the spectrum.
- Spectrum sharing: Providing fair spectrum sharing among coexisting users.[3:2128]

With these capabilities the cognitive radio is able to open a connection for the user and maintain it in a changing spectrum. In Figure 11 the concept of this dynamic spectrum access is visualized.

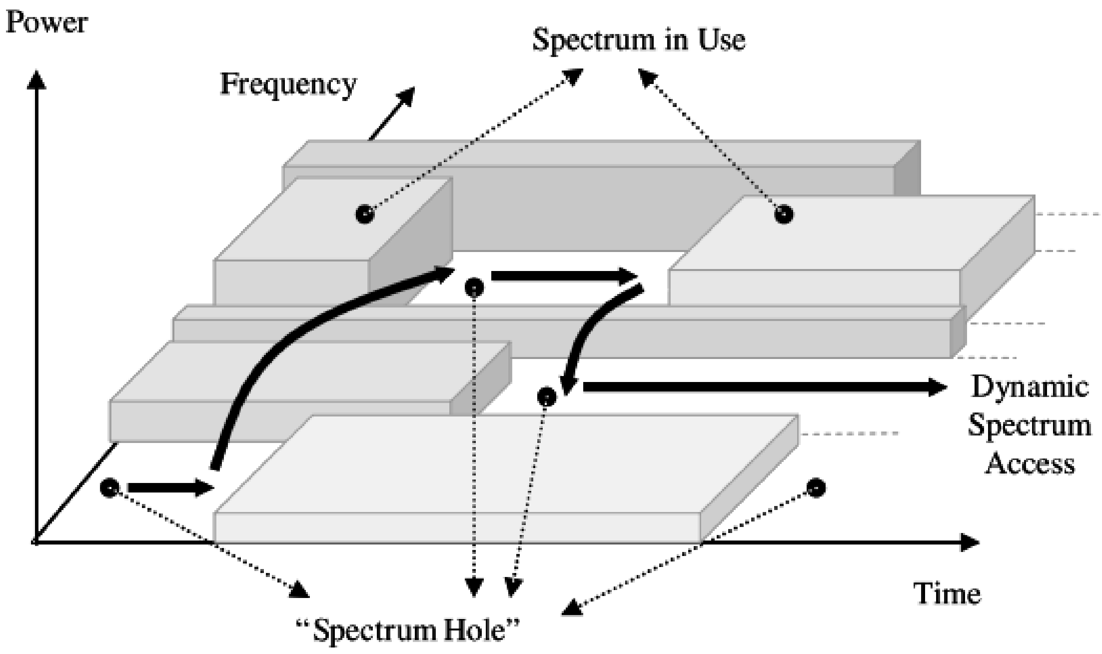

Figure 11. Dynamic spectrum access and spectrum holes. [3:2130]

The figure shows how the connection created by the cognitive radio hops from one frequency band to another to maintain constant connectivity. Even if a certain frequency band might appear to be free when the connection is made, this can change fast as the licensed user, one paying for the frequency use, might need the frequency. As cognitive radios are only secondary users in the spectrum, they then need to find a new free band or change their transmission power level or modulation to avoid interference. [3:2130]

The decision making process of a cognitive radio responsible for spectrum sensing, analysis and access is called the cognitive cycle. It is discussed next.

2.4.3 Cognitive Cycle

Cognitive radios need to interact with their surroundings in real time to be able to adapt to the changes in the environment. Figure 12 illustrates this process.

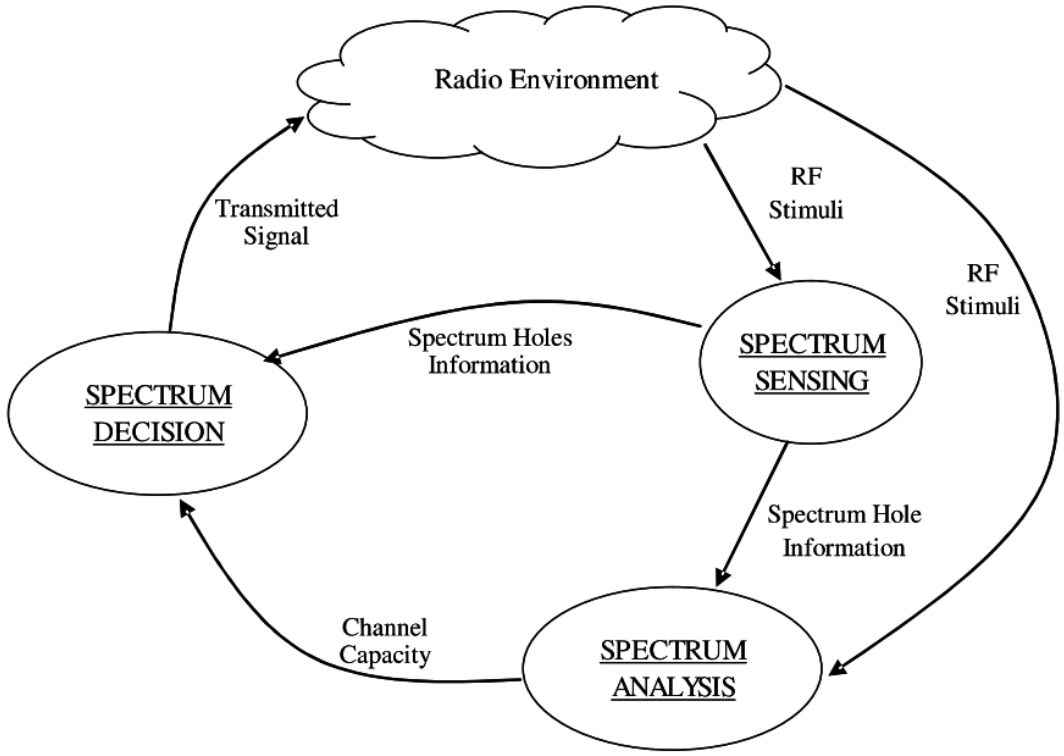

Figure 12. Cognitive cycle. [3:2132]

As the figure shows, the outside world provides RF stimuli, based on which the cognitive radio detects spectrum holes i.e. white space. There are several ways this spectrum sensing can be done.

Transmitter detection basically means the cognitive radio is trying to detect an incumbent (authorized to operate on a given frequency band with regulatory priority) [1:10] transmitter signal in a certain part of the spectrum. This can also be done in several ways.

In matched filter detection, when the incumbent signal is a known signal, the cognitive radio uses pilot signals, preambles or word or spreading codes for coherent detection to determine whether the incumbent signal is present or not. [3:2138] If the incumbent signal is not known, energy detection is used. This however presents some challenges, as this only confirms the presence of a signal, not the fact that it is an incumbent signal. [3:2139] Another way of detecting the presence of a signal is cyclostationary feature detection. The spectrum is analyzed and manmade signals which generally have redundancy due to signal periodicity stand out from the random noise. This provides better results than simple energy detection, but is computationally complex and also requires a long observation time. [3:2139]

In Cooperative detection the individual local detections made by cognitive radios are used to determine whether or not an incumbent signal is present. This is theoretically more accurate than individual detection, since it provides more reference material on the matter. The detection can be done in a centralized manner, where a base-station in the area gathers all sensing information and passes it along to cognitive radios. Another way is the distributed method, which requires direct exchanges between the cognitive radios. [3:2140]

Interference-based detection offers new possibilities to implement cognitive radios. As the interference is noticed i.e. takes place at the receiver, Federal Communications Commission (FCC) has introduced a new way of measuring interference, the interference temperature. [3:2141] This approach to defining interference is displayed in Figure 13.

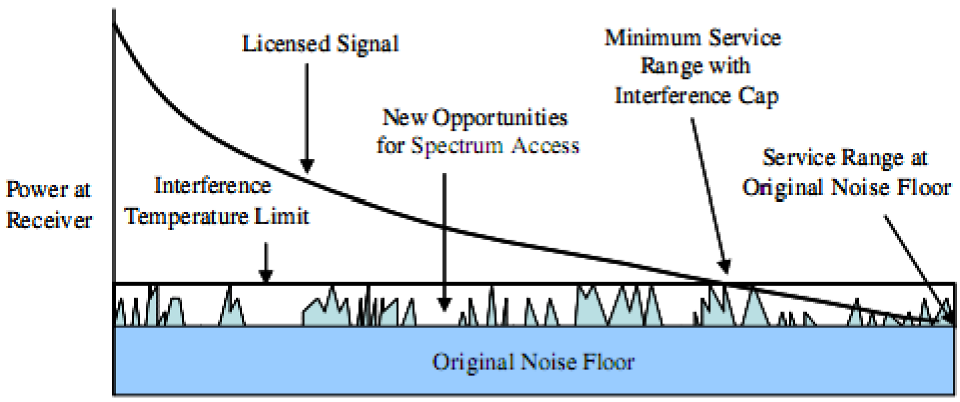

Figure 13. Interference temperature. [3:2141]

As can be seen in the figure, the noise floor rises in several position when additional interfering signals are introduced. The interference temperature model counters the effect of additional interference by introducing interference temperature limit at the receiver. This limit represents the amount of interference the receiver is able to tolerate. [3:2140]

As long as cognitive radios stay under this limit, they could operate in the otherwise vacant portions of the spectrum. There are challenges to this model, if the cognitive radio is unaware of the location of the local incumbent users, this method cannot be used to measure interference. [3:2141]

After having done the spectrum sensing, the spectrum hole information is then used to determine which of the available spectrum bands best suit the needs of the user. Several characteristics of the spectrum holes need to be taken into account when making the decision:

- Interference varies from spectrum band to another, as some bands are more heavily used than others. This in turn dictates the power level the cognitive radio is allowed to use without causing interference. This furthermore affects the capacity in that particular channel.
- Path loss is greatly dependent on the frequency, so the choice of spectrum band affects this greatly. To compensate for the increased path loss more transmitting power would need to be used. This is not always permitted as it would cause more interference. It would also use more energy.
- Wireless link errors depend on the modulation and interference. If interference is high, only low order modulation can be used to minimize the errors.
- Link layer delay can vary greatly from spectrum band to another. To manage the forementioned interference, path loss and wireless link errors, different link layer protocols need to be used, resulting in varying amounts of delay.
- Holding time is the expected time for which the cognitive radio can use the licensed spectrum before interruption. It is dependent on the incumbent user. Longer holding times increase the quality of connection, as switching from one spectrum band to another always causes some disruption. [3:2142]

After all spectrum holes are analyzed, the information is then used to make a decision which spectrum band to use. The quality of service requirements of the user need to be taken into account here. Based on user requirements the data rate, acceptable error rate and delay, the transmission mode and bandwidth can be set. [3:2143]

Due to the nature of spectrum use with cognitive radios, a change of operating frequency is more than likely to take place. This process is explained further in the next section.

2.4.4 Spectrum Mobility

Spectrum mobility is the process when cognitive radio changes the frequency at which it operates. According to the fair spectrum sharing policy mentioned earlier, the aim is to provide each cognitive radio the best channel available. The need to change a spectrum band may be caused by channel conditions getting worse or a licensed user appears on the channel. Another cause could be the device itself moving from the area of one base station to another, and the available spectrum bands are different in the new location. [3:2145]

As the cognitive radio changes the operating frequency, the network protocols shift from one mode of operation to another. Spectrum mobility manager attempts to make sure the transition is as smooth and fast as possible to ensure the active applications do not suffer during spectrum handoff. The sensing algorithm provides information about the duration of the spectrum handoff and mobility management protocols take action to minimize the effect on ongoing communications: TCP connection can be put to a wait state while new TCP parameters are not available, for data communication, packets sent during spectrum handoff should be stored and transmitted after the connection is available again. [3:2144]

As other users sharing the spectrum are an integral feature in the world of cognitive radio, spectrum sharing and various ways of implementing it are discussed in the following section.

2.4.5 Spectrum Sharing

Spectrum sharing is a process that can be divided into five separate steps. First these five steps are discussed, later in the section also the different methods of implementation are covered.

- Spectrum sensing: This was already discussed in detail in section 2.4.3. As was stated, to be able to access the spectrum the cognitive radios first need to be aware of the usage of local spectrum. [3:2145]
- Spectrum allocation: Depending on the spectrum allocation policies, internal or external, the cognitive radio can then allocate a channel. [3:2145]
- Spectrum access: As there are multiple users and devices competing for the same spectrum allocation, the access should be coordinated to avoid collisions in the spectrum. [3:2145]
- Transmitter-receiver handshake: This is done to make sure also the receiver is aware of the conditions and the selected spectrum. [3:2146]
- Spectrum mobility: Since cognitive radios are only secondary users of the spectrum, the change of spectrum band is likely to happen. There is a need for spectrum mobility to provide efficient way to continue the communication in another vacant part of the spectrum. [3:2146]

There are several ways of implementing spectrum sharing techniques. They can be categorized by architecture, spectrum allocation behavior and spectrum access technique.

Architecture can be either centralized or distributed. In centralized sharing a centralized instance controls the spectrum allocation and access. To help this solution to work, a forementioned distributed sensing procedure could be used to provide more information to the central node. In distributed sharing each device is responsible for spectrum allocation and access based on policies in effect. [3:2146]

Spectrum allocation behavior can be cooperative or non-cooperative. Cooperative solutions require communication and interference information sharing among the local devices attempting to make their connections. Centralized solutions are all regarded as cooperative, but even some distributed solutions can be regarded as cooperative. [3:2146] Non-cooperative solutions are only concerned about the one device in question. Due to lack of negotiation with other devices, the spectrum utilization as a whole may suffer, but as a tradeoff the device itself could gain a better connection. [3:2147]

The division in spectrum access technique is between overlay spectrum sharing and underlay spectrum sharing. In overlay sharing technique the device connects to the network using part of the spectrum that is not used by licensed users. Underlay sharing is markedly different, as the device begins transmitting with a transmit power that is considered to be noise by the licensed users. To make this work, spread spectrum techniques need to be utilized. As a reward however, increased bandwidth compared to overlay techniques is available. [3:2147]

This study focuses on cognitive radios working on television white space frequencies. The following section discusses television white space and its causes.

2.5 Television White Space

The International Telecommunication Union (ITU) has divided the world into three regions for frequency allocation. Since the measurements in this study take place in Finland, this section also uses Finnish television broadcasting network as an example. In region 1 of worlds frequency allocation, consisting of Europe, Africa, Middle-East and Russia [7:5], TV transmissions are given the frequency ranges 47 - 68 MHz and 174 - 790 MHz. [7:308]

One cause for television white space is in the structure of the terrestrial television broadcasting network. There are several factors at play that cause the transmitted signals to have a very long range:

- Relatively low frequencies: VHF (very high frequency) band and lower part of the UHF (ultra high frequency) band ranging respectively from 30 MHz to 300 MHz and 300 MHz to 3000 MHz. [7:3]
- High antennas: The transmitting antennas are regularly on a 100 m to 300 m high mast. [7:309][5]
- High transmitting power: Equivalent isotropic radiated power (EIRP), i.e. if the power would radiate equally to all directions, as high as 1000kW is used for TV transmissions. Usually the EIRP is a few tens of kilowatts. The real transmitted power is however lower due to the directivity of the antennas. [7:309]

This design is necessitated by the fact that television transmissions need almost clear line of sight path from transmitter to receiver. One transmitter station can cover usually an area with a radius of roughly 70 km. The signal can however be received often at ranges 20 to 30 km greater than this [7:309] This requires safety margins to ensure transmissions done with same frequency do not interfere each other. These safety margins provide a localized opening in spectrum and place for cognitive radios to use, the white space. Figure 14 illustrates the terrestrial TV transmission network in Finland.

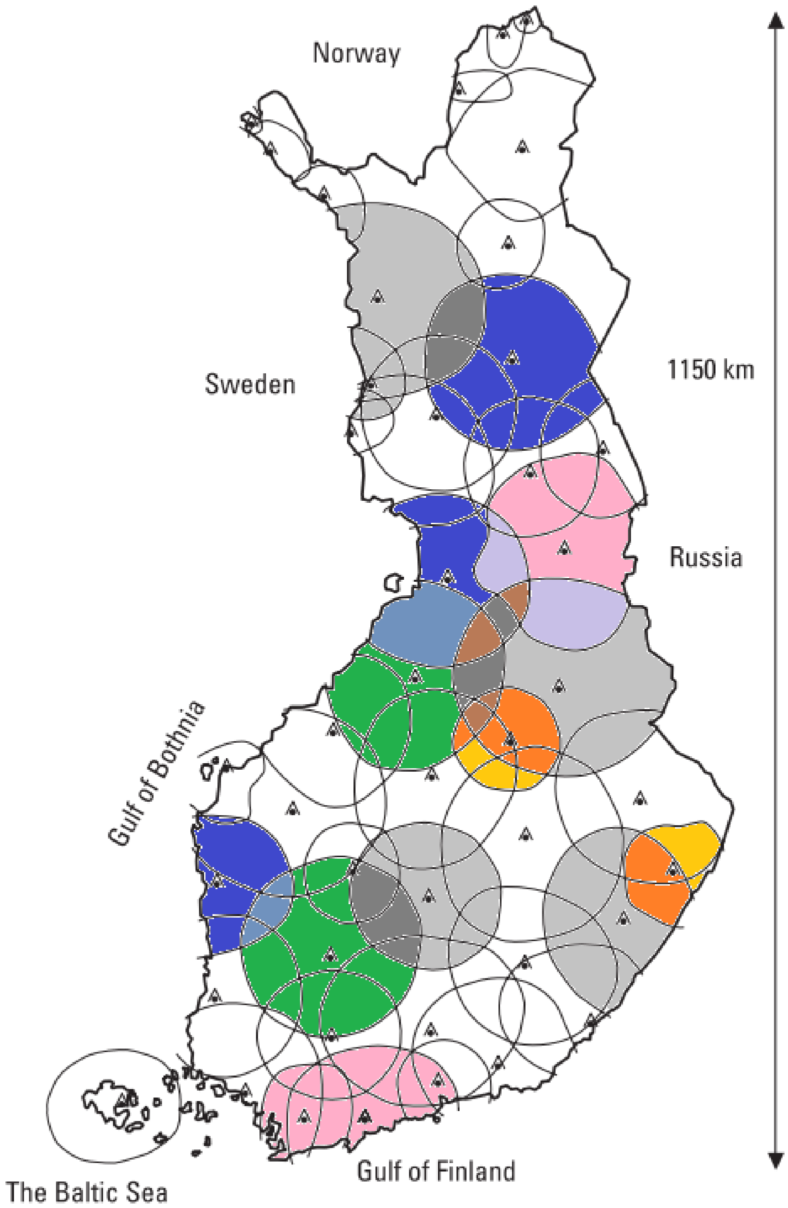

Figure 14. Terrestrial TV transmission network coverage in Finland. [7:310]

Figure 14 has been colored for illustrational purposes according to frequencies used by particular transmission stations. [5] As can be seen, the reuse of frequencies done with relatively large safety margins between the areas with same frequency. The channel bandwidth for TV transmissions is 8 MHz, and with this bandwidth four to five TV channels can be transmitted. [7:308] Noteworthy is that transmission stations marked in the figure are only the major transmission stations. In addition to these, there are several minor transmission stations that are used to relay the signal received from a major station, convert it to a different frequency and then retransmit it. [7:309] Also notable is that the coloring was done based on information about channel bundles A and B. Complete and updated list of all transmission stations and channel bundles is available from Digita. [5]

The other cause for television white space could be the transition to digital television. [4:6] This is true only if spectrum is actually freed in the process. Depending on the implementation, it could actually make the spectrum usage more efficient and thus reduce opportunities for TV white space use.

The next main section focuses on the purpose of the measurements, the equipment used and tests conducted prior to the main measurements themselves.

3 Setup and testing

The following sections go through the setup, hardware and software, and the pre- and post-measurement testing. The data recorded during test measurements is included in Appendix 1.

3.1 Setup

Most of the equipment for the study was provided by Nokia corporation, this included the laptop used in the testing and measurements, the white space devices (WSD) themselves and the pre-configured router. A WLAN access point and some additional measurement software to monitor the WLAN adapter on the laptop were also needed. Figure 15 displays the general television white space network structure of the setup and the necessary components.

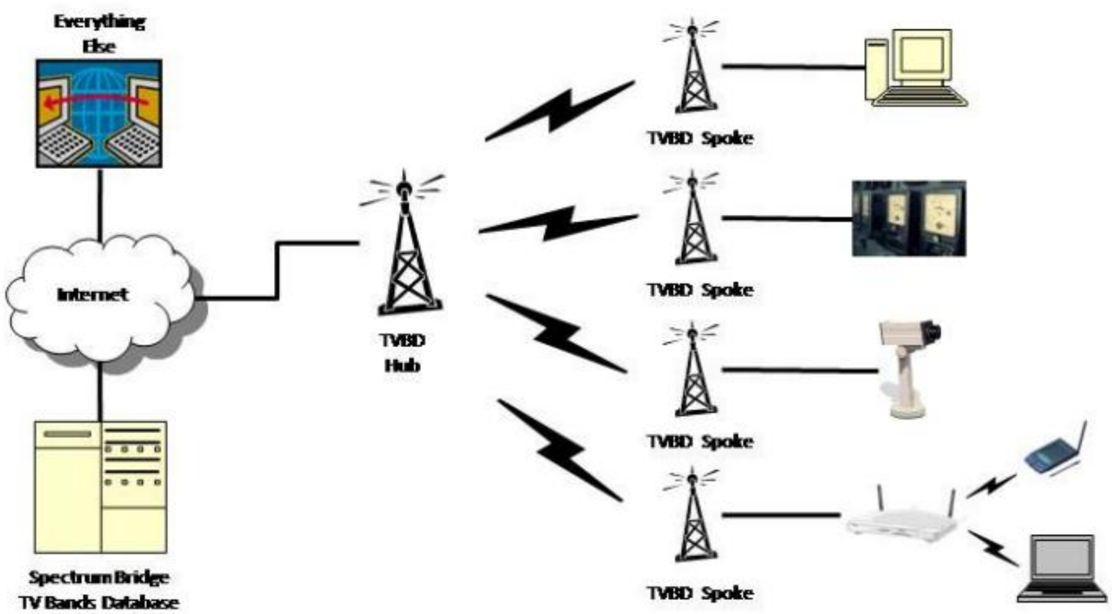

Figure 15. TV White space network structure and necessary components. [4:11]

As the figure shows, a database is used to control the spectrum access of the white space devices, this is in effect a utilization of centralized architecture, as mentioned in section discussing the cognitive radio. TVBD noted in the figure means television band device which is the same as white space device. [4:9]

The devices themselves are not intelligent. They have preset location information and preferred frequencies they attempt to operate on. Operation is only possible if the devices get a connection to the database, and the usage of the frequencies attempted to use is allowed for that location.

When a configured WSD hub is powered on, it attempts to connect to the database over the internet to receive a channel map. After receiving it, the hub selects a preferred frequency and starts transmitting a beacon message. [4:12]

When a spoke is powered on, it starts to listen to a beacon message on all available channels of its radio frequency range. Before requesting a hub to join a network, the spoke transmits nothing. After being accepted to a network, the spoke is given coordinated transmit opportunity according to a polling mechanism controlled by the hub. The spoke then needs to access the database to receive its own channel list. Spoke will then verify the channel used by the hub is available in the spokes location. If not, the channel is abandoned and the scanning procedure is restarted. [4:12]

The management of the white space devices can be initially done only by direct connection to the device. After the properties of the radio have been set, it can also be accessed remotely over the network. Configuration is done with TVBD management software that was installed on the laptop provided by Nokia.

Contrary to Figure 15, a preconfigured router was used between the hub device and the internet. This was done to provide static IP addresses to the white space devices and DHCP (dynamic host configuration protocol) functionality to the devices connecting to the WS WLAN.

3.1.1 Hardware

Five TV white space devices were provided. One of the devices was preconfigured to operate as a hub for the other devices called spokes. There is no physical difference between hub and spoke devices, only one setting done by the control software is different. Figure 16 illustrates the components directly related to the WSDs.

Figure 16. White space device. [15]

In Figure 16 the white space device can be seen in parts and assembled with a power supply unit. Each device has four connectors: BNC female connector for the antenna and a male DB-9 serial connector on the top. A 12 volt DC power connector and RJ-45 connector are located on the right hand side of the box. Also on the right hand side are the diagnostic LEDs. [4:22] The proclaimed values for the transmitter and the sensitivity of the receiver were respectively 32 dBm and -97 dBm. [4:21] The supplied antennas were 30,5 cm long, which is not quite the half-wave length required of an efficient antenna for a 618 MHz frequency. The half-wave length of the antenna would have been 24,3 cm.

The power supply units were equipped with United States standard power plugs, so adapters were needed to convert them to the Finnish standard. Figure 17 displays the router used for DHCP and static IP allocation.

Figure 17. DHCP router and US standard power strip. [15]

As can be seen in the figure, also the router had a US standard power supply unit, so a power strip with slots for US standard plugs was used at the location where the router and most stationary devices were located.

For reference measurements a WLAN access point was provided by Metropolia. This device was Buffalo Nfiniti WHR-G300N wireless router and access point. The access point was able to support IEEE 802.11n/g/b compliant devices in the 2.4 GHz frequency range. [16:25] The IEEE specified maximum transmit power for the device was 100 mW (20 dBm) [17:524] and the sensitivity of the receiver -85 dBm. [17:525]

Lenovo T41 -laptop computer was provided to be used as a mobile measurement station for simultaneous measurements of the RSSI values of the spoke WSD connected to the laptop and the WLAN adapter of the laptop. Figure 18 displays a laptop with a spoke equipped with a battery for mobile use.

Figure 18. Laptop with a mobile spoke. [15]

Due to the laptop and its battery both being relatively old, an extension cord was needed during the measurements to keep the laptop running.

The measured RSSI values were read using TVBD Element Manager for the white space device and Homedale::WLAN Monitor for the WLAN adapter. The main features of these applications are discussed in the next section.

3.1.2 Software

TVBD Element manager was used to manage and monitor the white space devices in the network. The devices were preconfigured with an IP address and the and the list of devices was static even if some of the devices were not in use. The radio frequency (RF) configuration tab of the software is shown in Figure 19.

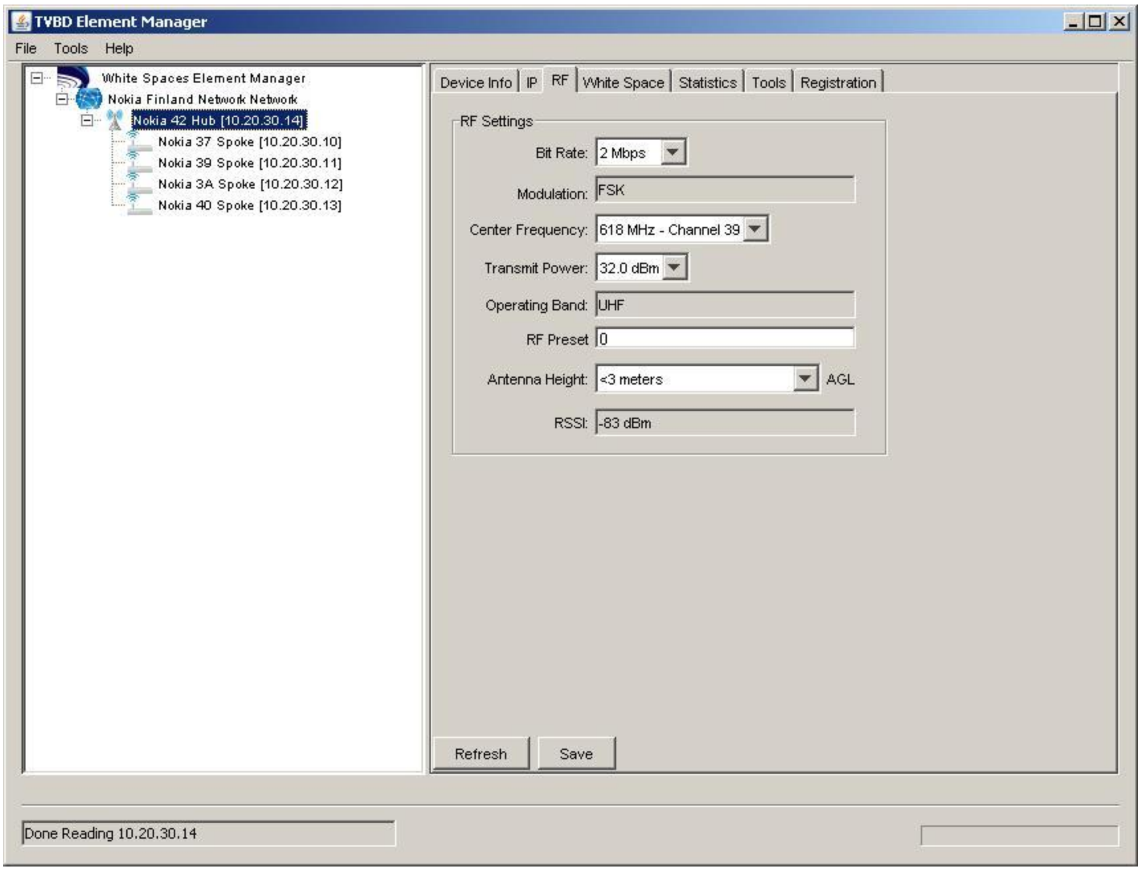

Figure 19. TVBD Element Manager RF tab.

As can be seen, the bit rate was set at 2 Mbps and could not be changed into anything else. Modulation used was FSK, and also that could not be changed. The controllable parameters were the center frequency and transmit power. Changing the center frequency would however be of no use, as the permitted frequencies for the location were limited, and the database would not permit the use of other frequencies.

RSSI value could also be read from the RF tab. To update the value clicking of the refresh button was needed. When the software had done updating the information, lower left hand corner displayed Done Reading and the IP address of the node that was read. Normally this worked rather fast, so updating of the RSSI could be done several times in a second if needed.

If the application was used to access unused WSD or the connection to the device could not be established, lower left hand corner displayed a message Connection Failed.

In Figure 20 the White Space tab of the management software is displayed.

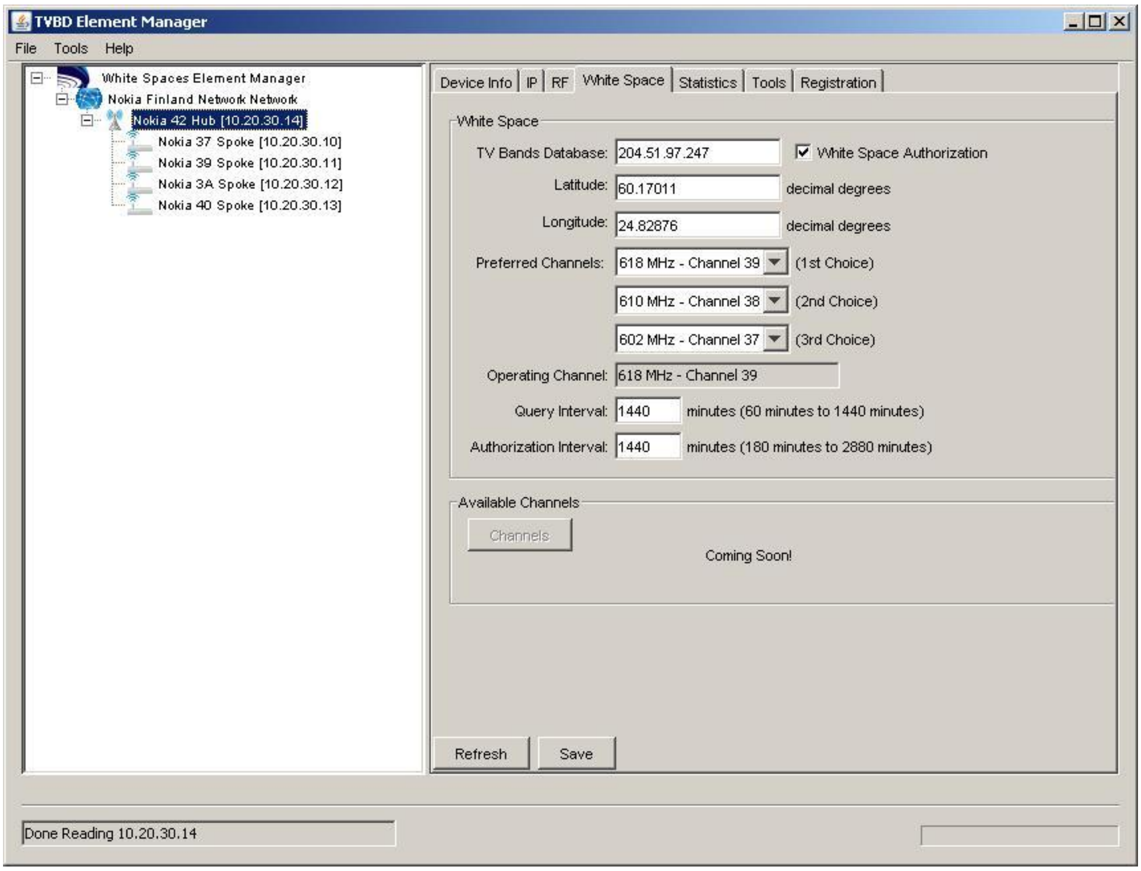

Figure 20. TVBD Element Manager White Space tab.

On the white space tab the IP address of the control database could be found and changed if needed. Also the location information in the form of latitude and longitude could be set here. Three preferred channels for the device could also be set on this tab. All the necessary information was already preconfigured here.

On the IP tab the IP related information of the device in question could be changed and monitored.

While the white space tab was arguably more significant for the functionality of the setup, RF tab was more necessary and more heavily used for completing the measurements.

Homedale::WLAN Monitor is a freeware software developed by the SZ development. [18] In Figure 21 the access points tab of the application is displayed.

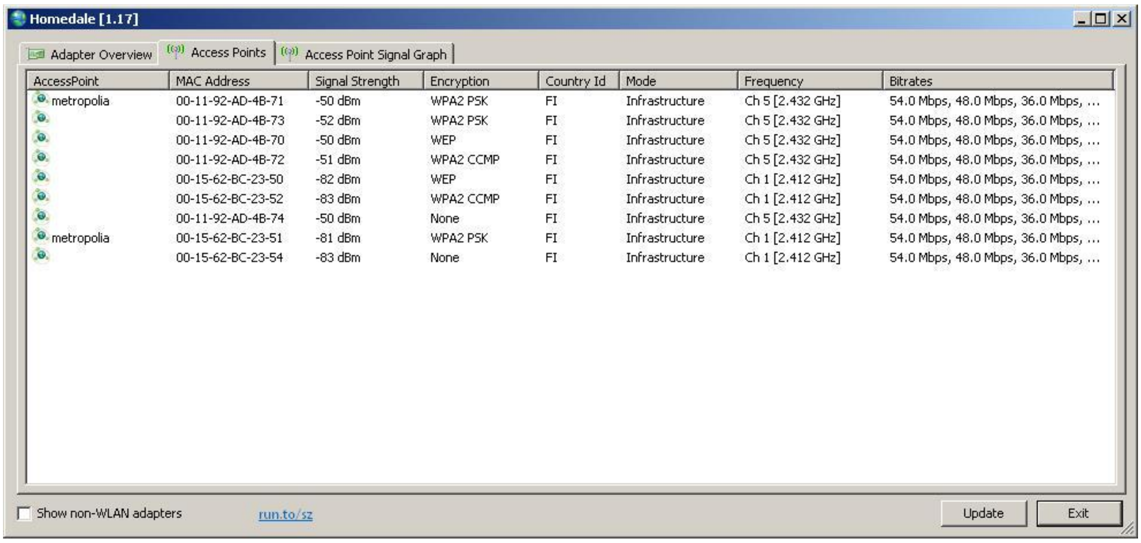

Figure 21. Homedale::WLAN Monitor access points tab.

The access points tab lists all WLAN access points detected by the WLAN adapter. The list is "live" but also an update button for manual updates was provided. As can be seen, the information shown for each access point include the SSID (service set identifier) or the network ID of the access point, signal strength, encryption and frequency and bit rate.

The following sections discuss the testing done prior to the measurements and also another run of tests done for verification purposes after the measurements.

3.2 Wired Tests

The initial testing of the equipment used for the study was conducted at the Helsinki Metropolia University of Applied Sciences. The test equipment consisted of two television white space devices, a hub and a spoke, a laptop computer with TVBD Element Manager installed to access and control the white space devices and a spectrum analyzer. Adjustable and fixed attenuators and coaxial cables were also used. The tests were conducted to verify that readings given by the TVBD Element Manager correspond with the real received power level.

Since the permit to use television white space frequencies for aerial transmission did not cover the Metropolia premises, testing was done using wired connection and attenuators instead of the wireless connection. Figure 22 displays the attenuators used in the testing.

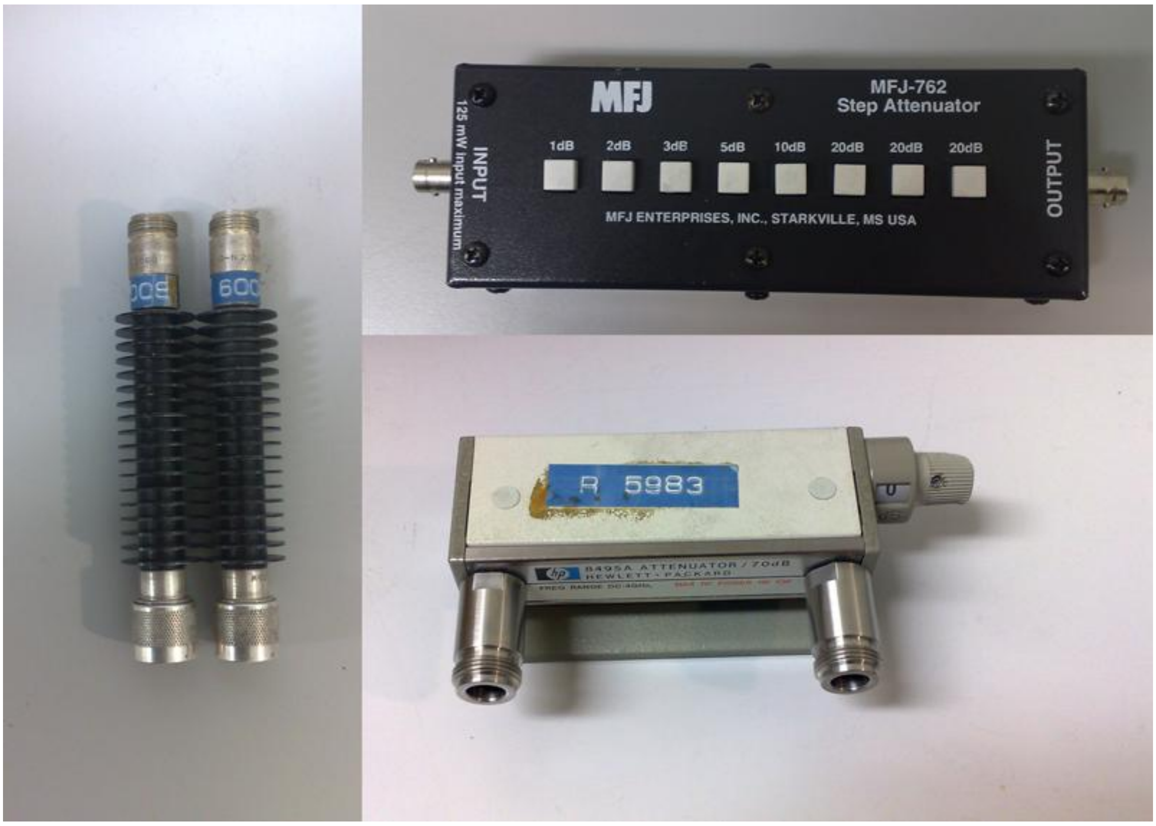

Figure 22. Attenuators.

On the left the pair fixed 20 dB attenuators can be seen. On the right are the two step attenuators used in testing. The upper MFJ attenuator had controls with which to adjust the attenuation in 1 dB steps where as the HP attenuator had 10 dB steps with a maximum attenuation of 70 dB.

The measurements were done using the TVBD Element Manager and a spectrum analyzer. Due to limitations in input power for both the spectrum analyzer and the step attenuators, the two solid 20 dB attenuators were connected in series to the hub WSD before connecting any other attenuators or measurement devices. Both step attenuators were also connected.

As a reference, free space path loss at one meter distance was calculated.

$$FSPL = \left(\frac{4 * \pi * r * f}{c} \right)^2$$

With values 3,14 for π, 1 m for r, 618000000 Hz for f and 300000000 m/s for c the formula returns 669,44. This was transformed into dB using the following formula:

$$P_{dB} = 10 * \log_{10}(P)$$

The value used for P was 669,44, and the formula returned a value 28,3 dB, giving thus the free space path loss for one meter distance at 618 MHz frequency.

With 32 dBm transmit power and 40 dB worth of fixed attenuators, other attenuators (with zero attenuation selected), cables and connectors in the transmission line, the predicted received power was around -10 dBm. TVBD Element Manager gave the value -14 dBm and the spectrum analyzer -14.33 dBm.

Measurements were taken at 1 dB intervals and recorded in an Excel sheet. The MFJ step attenuator was used to select the attenuation level. In initial testing, even if the HP step attenuator was installed in series after the fixed attenuators the value was left as 0 dB. Figure 23 displays the results of the initial measurements as graphs. The recorded measurement data can be found in Appendix 1.

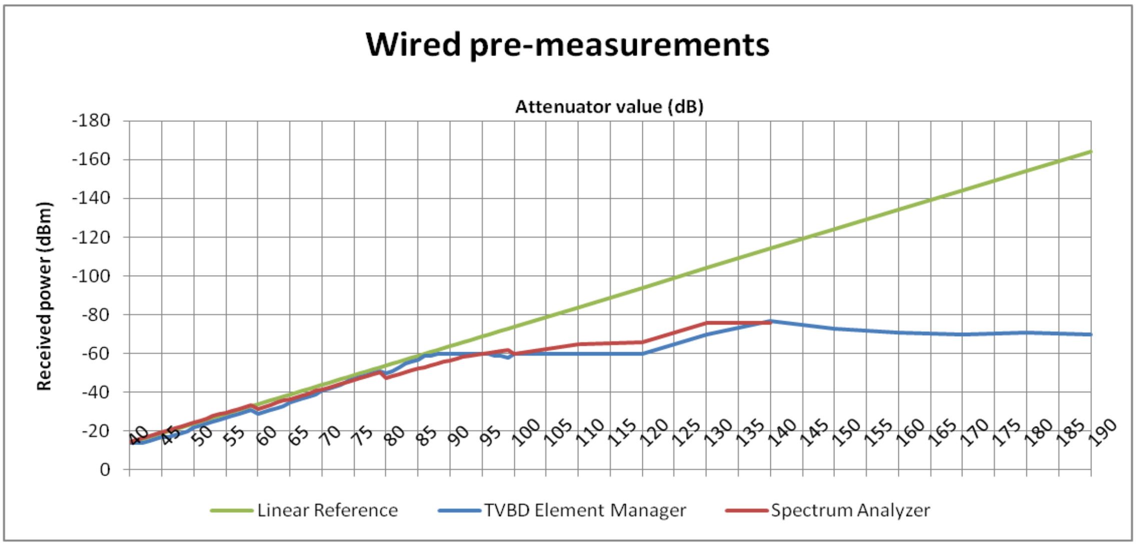

Figure 23. Wired pre-measurements.

As can be seen from the graphs, both spectrum analyzer and TVBD Element Manager (TVBDEM) measurements follow the linear trend relatively well in the beginning. Every 20 dB there is a noticeable dip in both measured graphs. This was caused by combining fragmental increases in HP step attenuator into one 20 dB step. Dip in the graph translates to increased received power, which in turn means the attenuation of the 20 dB singular step was less than the partial attenuator steps combined.

Up to 80 dB attenuation the behavior in both measurements could be characterized as consistent. After this point the measurement done with spectrum analyzer starts to deviate more and more from the linear reference. Also TVBDEM started to display strange results.

After reaching received power reading of -60 dBm, which happened at 88 dB attenuation, the TVBDEM reading remained -60 dBm despite the increase in attenuation. When attenuation was increased to over 120 dB the reading started to decrease again, only to peak at -77 dBm at 140 dB attenuation. After this the value started to increase to level around -70 dBm. Roughly at 130 dB attenuation the signal could not be distinguished from the noise floor of around -76 dBm with the spectrum analyzer. Beyond 100 dB attenuation 10 dB steps with the MFJ attenuator and beyond 120 dB 10 dB steps of the HP attenuator were used.

Initially the reason for the level measurements and somewhat unexpected behavior was deduced to be caused by leakage of power from some of the connectors or the transmitting device itself. This would have been compounded by the close proximity of the transmitter and receiver. All the devices were kept on same table less than one meter apart. This theory was supported by the fact that despite the white space devices had a theoretical reception sensitivity of -95 dBm, internet browsing was possible with a laptop connected to the spoke with as much as 190 dB attenuation on the transmission line.

Further wired tests were planned to validate the data. In these tests longer coaxial cables were used to connect the devices, and additionally the receiver was taken into a radio shielded room while the transmitter was left outside. In the second round of wired tests no spectrum analyzer was used to measure the power level. Figure 24 displays the measurement results as graphs. Recorded data from these measurements can also be found in Appendix 1.

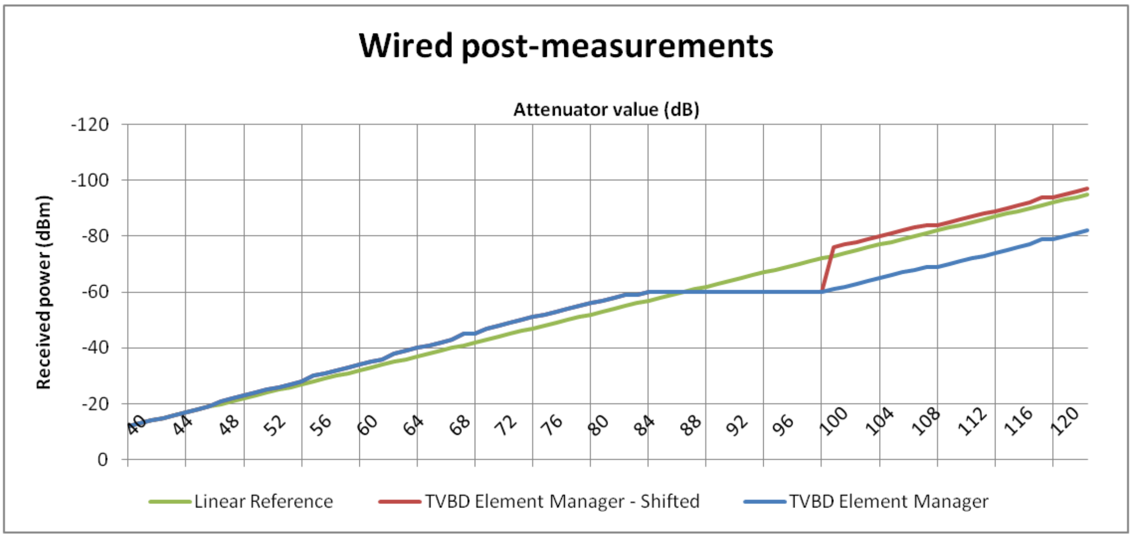

Figure 24. Wired post-measurements.

The measurement graph follows the linear reference relatively well, maximum deviation being 4 dB. This continues to the point where the measured attenuation reaches -60 dBm with the attenuator value at 85 dB. After this point the indicator for received power remained at -60 dBm for an additional 15 dB attenuation increase, after which the RSSI value started to decrease again in a relatively linear manner from -60 dBm.

A corrected graph is included in the figure to demonstrate how well the measurement graph actually follows the linear reference aside from the flat line at -60 dBm. The corrected values were decreased by 15 dB to account for the increased attenuation during the flat line phase. The flat line was 16 dB long in total, but one measurement value was left as a real one for the 85 dB attenuation mark. The relatively small deviations from the reference may have been caused by attenuator inaccuracy or slight calibration errors in the equipment. As the deviation was not significant, no other counter calibration besides the fixing of the flat line effect was deemed necessary.

With only the fixed 40 dB worth of attenuators active the received signal strength was -12 dB. Transmitting power was 32 dBm. The total attenuation was 44 dB, so the cables, connectors and inactive attenuators amounted to an attenuation of 4 dB. After

123 dB attenuation the connection was lost. The final RSSI value recorded was 82 dBm which as a fixed value is -97 dBm. This corresponds well with the reported receiver sensitivity of -95 dBm.

The following section discusses the wireless test measurements done at the Metropolia premises.

3.3 Wireless Test

Wireless tests at Metropolia were conducted after the license to operate the white space devices wirelessly was extended to cover the Metropolia premises. The tests were done to ensure all equipment was functioning properly and establishing the wireless connection was possible.

A limited set of test measurements were done by taking a set of five measurements in each measurement location, varying the position and direction of the trolley carrying the measurement equipment. The received signal strength indicator values for the white space device and laptop WLAN adapter were then recorded in all five positions. An average RSSI value was then calculated for both connection types. Also downlink and uplink throughput for the white space device connection was measured at each location using www.speedtest.net when the connection was available. Table 2 displays the results of wireless tests.

Table 2. Wireless test results.

	WSD								**WLAN**					
#	no1	no2	no3	no4	no5	Ave	DL	UL	no1	no2	no3	no4	no5	Ave
1	-36	-33	-37	-36	-36	-35,6	1,67	1,48	-37	-34	-32	-36	-36	-35
2	-54	-43	-42	-48	-50	-47,4	1,69	1,54	-41	-44	-46	-38	-43	-42,4
3	-38	-43	-45	-45	-34	-41	1,68	1,65	-42	-42	-38	-36	-41	-39,8
4	-56	-56	-56	-54	-53	-55	1,68	1,57	-48	-56	-48	-52	-47	-50,2
5	-60	-60	-60	-54	-55	-57,8	1,69	1,66	-58	-56	-49	-63	-49	-55
6	-58	-58	-58	-60	-60	-58,8	1,68	1,66	-69	-61	-65	-61	-62	-63,6
7	-69	-70	-69	-72	-72	-70,4	-	-	-	-	-	-	-	-
8	-63	-68	-61	-70	-60	-64,4	1,68	1,55	-	-	-	-	-	-

The unit for all data under no1 to no5 and Ave headings is dBm. Ave signifies the average of measured RSSI values. DL and UL mark the downlink and uplink throughput measurements and the unit for them is megabits per second (Mbps). No further modification to the data was done. All -60 dBm values were left as they were, as the test was only a practice run for the actual measurements.

As a part of the wireless tests, a spectrum mapping of the WSD signal was done. Figure 25 illustrates the results of the spectrum mapping.

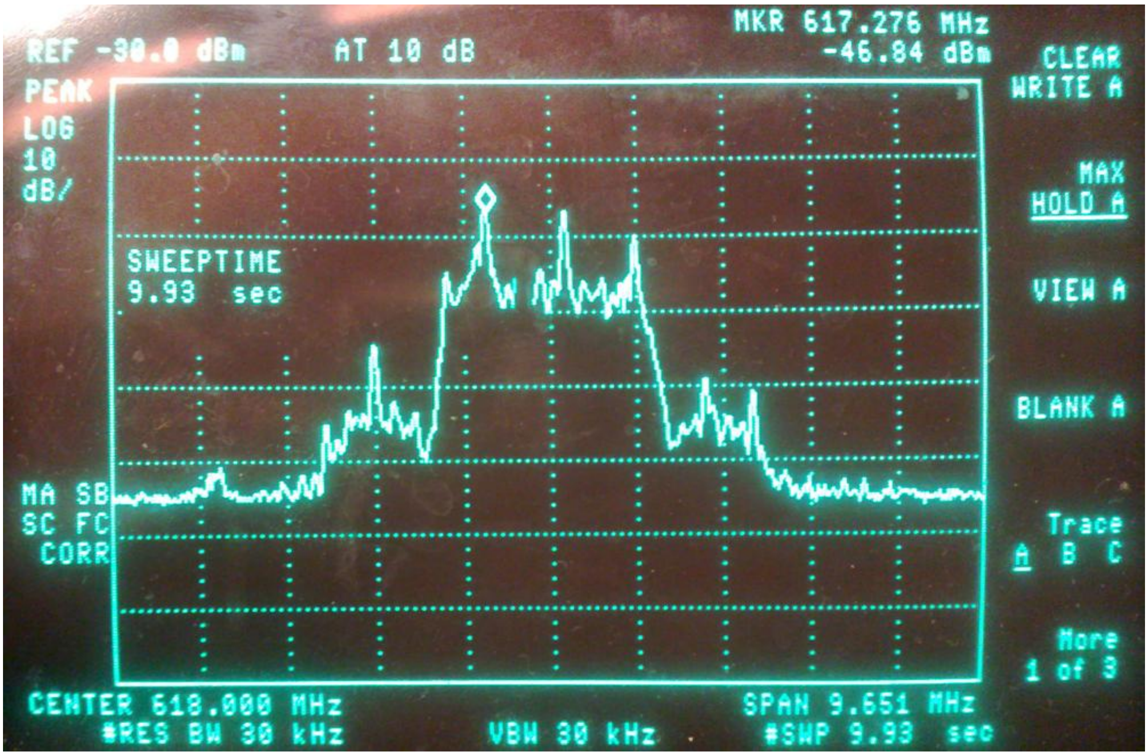

Figure 25. White space device spectrum.

Maximum hold functionality on the spectrum analyzer was used over several sweeps to record maximum values of the signal. The signal is centered on 618 MHz and has roughly 5 MHz bandwidth at -33 dB from the peak power.

The following section goes through the measurements conducted after the conclusion of the tests. Also measurement results are provided and discussed.

4 Measurements

This section discusses the measurements done in Helsinki at Nokia Research Center in Ruoholahti and Digita offices in Pasila. The results of the measurements are also displayed.

The method of the measurements was the same as was with the wireless testing. A set of five measurements were taken in each measurement location, varying the position and direction of the trolley carrying the measurement equipment. The received signal strength indicator values for the white space device and laptop WLAN adapter were then recorded in all five positions. An average RSSI value was then calculated for both connection types.

As the reception sensitivity of the white space device was -95 dBm according to the specifications, whenever the device failed to make a connection a value of -100 dBm was recorded. The specified minimum sensitivity of the WLAN adapter was -85 dBm. Whenever the WLAN adapter failed to detect the signal from the access point in all five measurements done at one measurement point, a value of -100 dBm was recorded for all measurements. If the adapter detected the signal in some measurements, the measurements with no detection were recorded with a value of -90 dBm.

The first measurement point was used as a reference point for both connection. Attenuation at that point was assumed as 0 dBm for both connections. The real average RSSI value of this reference point was then subtracted from the average RSSI values in other measurement points providing comparative and relative attenuation values. In points where no measurement data was available a value of -80 dBm was used.

4.1 Nokia Research Center

The measurements at Nokia Research Center (NRC) were conducted over several days assisted and supervised by Nokia representatives.

The outer walls of the building are constructed of steel frames and glass panes. The glass in the panes used in the outer walls is mixed with iron. This causes the glass to better absorb heat and other radiation, causing higher attenuation. Heavier load bearing walls are found around staircases and elevator shafts. Walls between office rooms are lighter plaster walls. The building is characterized by a square lobby area extending to the roof of the building.

In addition to measuring the received power levels also a practical test of browsing the internet was done at each measurement point if the connection was available. Initially the plan was to conduct a connection speed test, but this was not feasible as the free access (no corporate firewall or policies) to the internet was provided with a 3G connection. The limited bandwidth of the connection could have affected the measurements.

The value -60 dBm, which could in reality have been anything from -60 dBm to -75 dBm, featured in five of the fourth floor measurement points and three of the third floor measurement points. As only one value of the five recorded at each point was compromised, that value was excluded from the calculation of the average RSSI for that location.

Reference values closest to the transmitters in fourth floor at NRC were -28,6 dBm for the white space device and -29 dBm for the WLAN.

The data recorded during the measurements at the Nokia Research Center is included in Appendix 2.

4.1.1 Fourth Floor

The transmitters were placed on the fourth floor of the Nokia Research Center. The location of the transmitters is marked with an X in Figure 26. All measurement points on the fourth floor are also numbered in the figure. A total of 47 measurement locations were visited on the fourth floor.

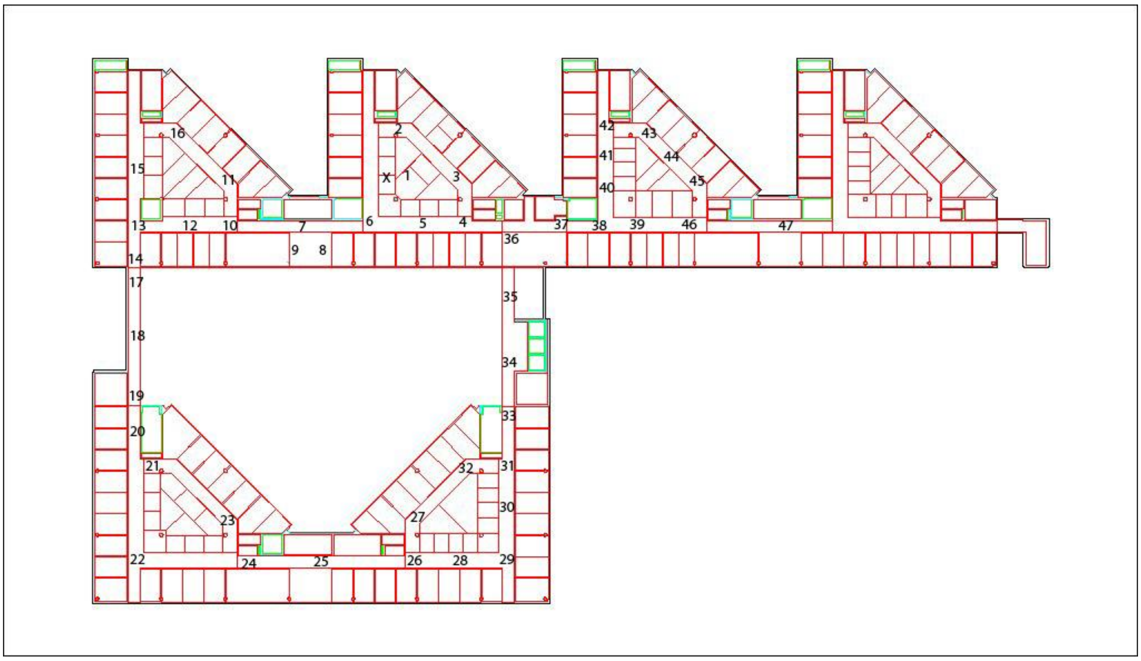

Figure 26. NRC 4th floor measurement points.

Elevator shafts and stairwells are marked with a greenish cyan color on the floor plan. These locations had generally sturdy supporting walls likely to cause higher attenuation. The triangular area in the middle of each wing was an open office area where as the rooms were separated from the corridors with glass walls. The open lobby area is visible through all floors in the lower part of the floor plan.

Figures 27 and 28 display the relative attenuation of both connections.

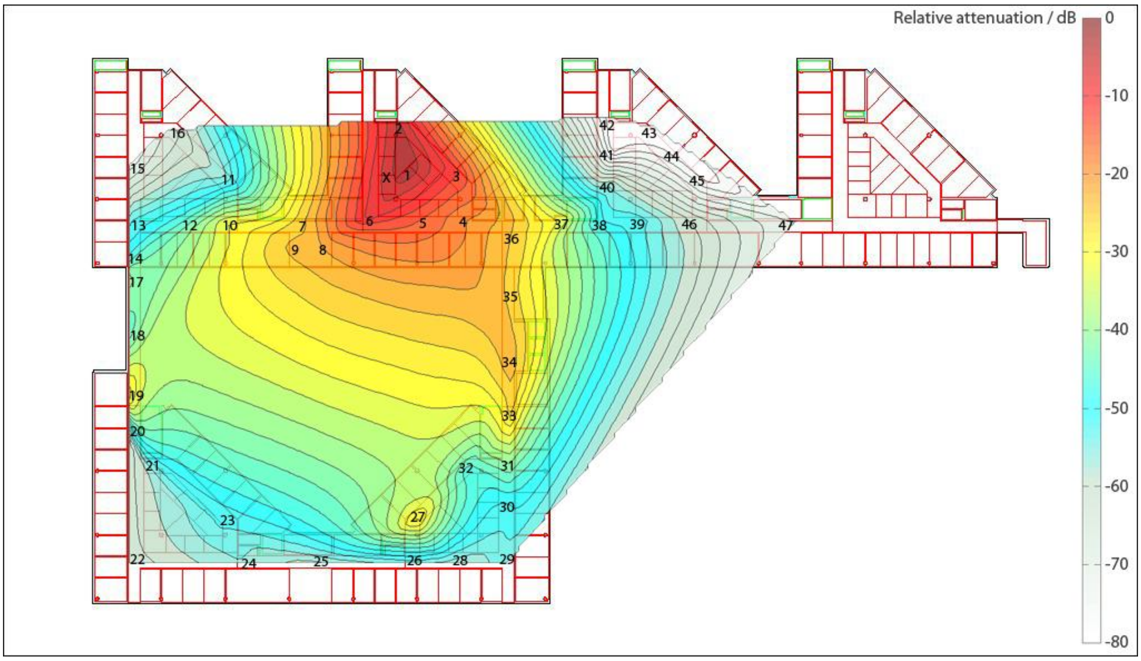

Figure 27. NRC 4th floor white space device relative attenuation.

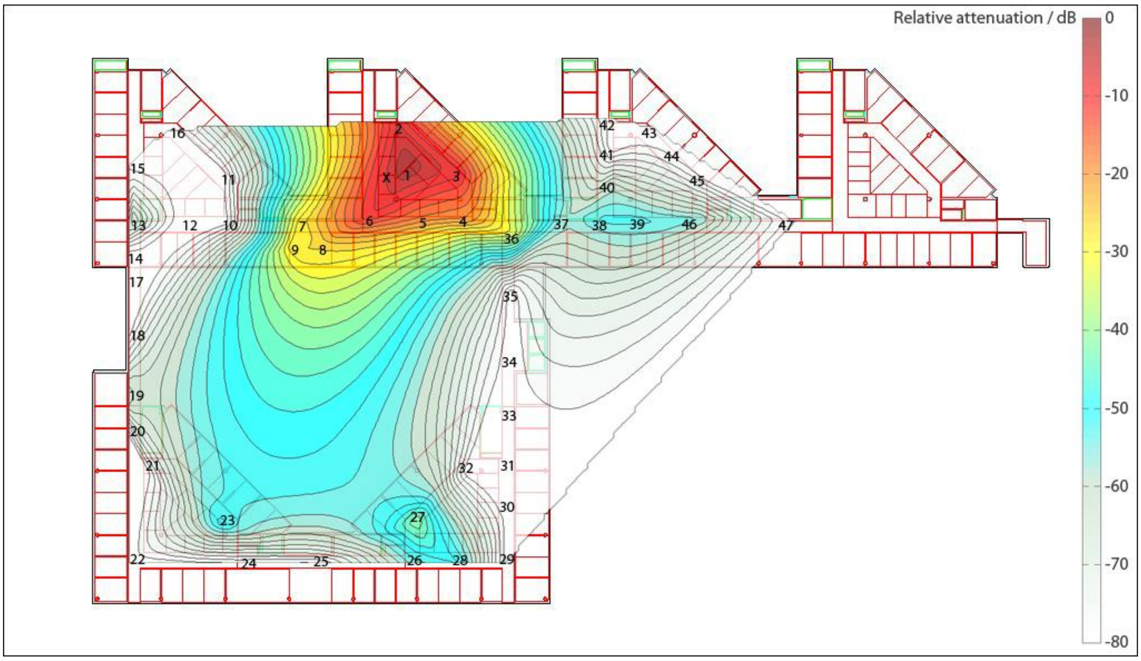

Figure 28. NRC 4th floor WLAN relative attenuation.

Initial assessment of the results indicate a lower attenuation and better coverage for the TV white space signal. In several locations the WLAN adapter failed to detect the signal altogether. In both figures the high attenuation caused by the outer walls is clearly evident and best seen in measurement points 10 to 16 and 40 to 45. The opening in the middle of the building caused basically only free space path loss enabling reception at a relatively long range. The islands of better reception across the lobby area were possible due to almost having a line of sight to the transmitters.

Figure 29 displays the difference between the two signals as a coverage map.

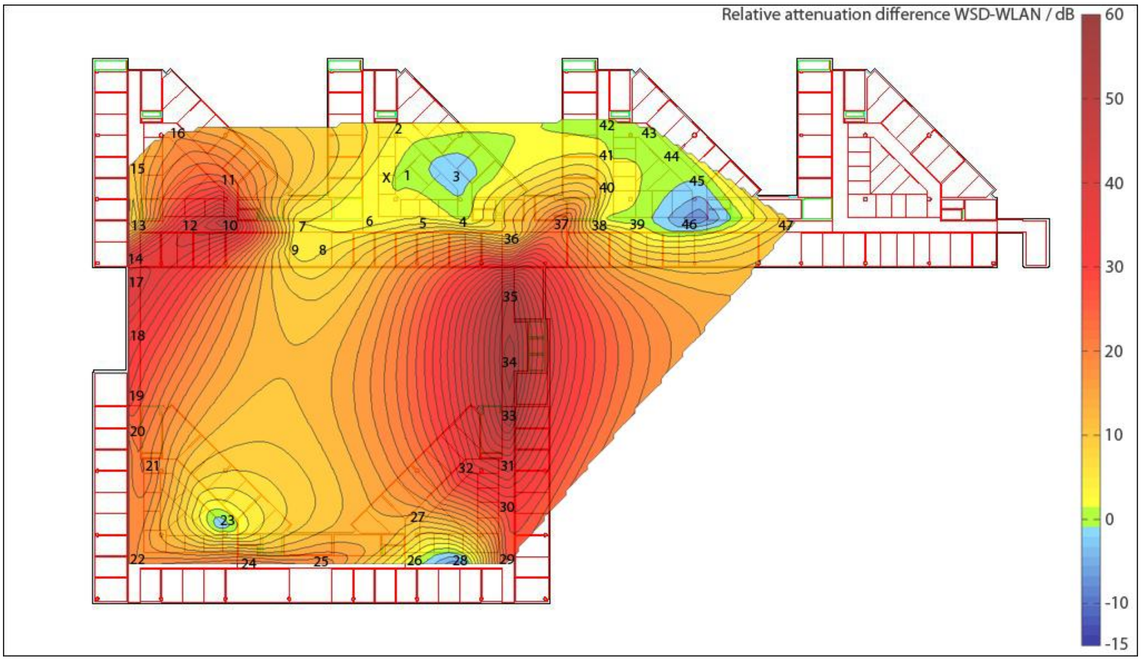

Figure 29. NRC 4th floor relative attenuation difference.

The relative attenuation difference was achieved by subtracting the relative attenuation value of the WLAN adapter from the relative attenuation value of the WSD. This method was used in all subsequent relative attenuation calculations. Colors from red to yellow indicate locations with less attenuation on the WSD connection, green indicates roughly equal attenuation and shades of blue indicate less attenuation on the WLAN connection.

These somewhat clear results in favor of the WSD can however be at least partially explained by the fact that at NRC during the measurements several dozens of WLAN access points were detected. Due to limited number of channels available at each station, and all stations sharing those channels, a distant and weakened signal gets overwhelmed by closer stations transmitting at the same channel. The number of measurement points where no WLAN signal was detected was 28 in the sixth floor.

Additionally in several locations only some of the measurements provided a detection. WSD connection was possible with internet browsing in all but measurement locations 15 and 16 and 41 to 45. As high as 58 dB attenuation differences were calculated.

4.1.2 Third Floor

Figure 30 displays the measurement points on the third floor at NRC. Included are also X and 0 marking the location of the transmitters and reference measurement point respectively on the fourth floor.

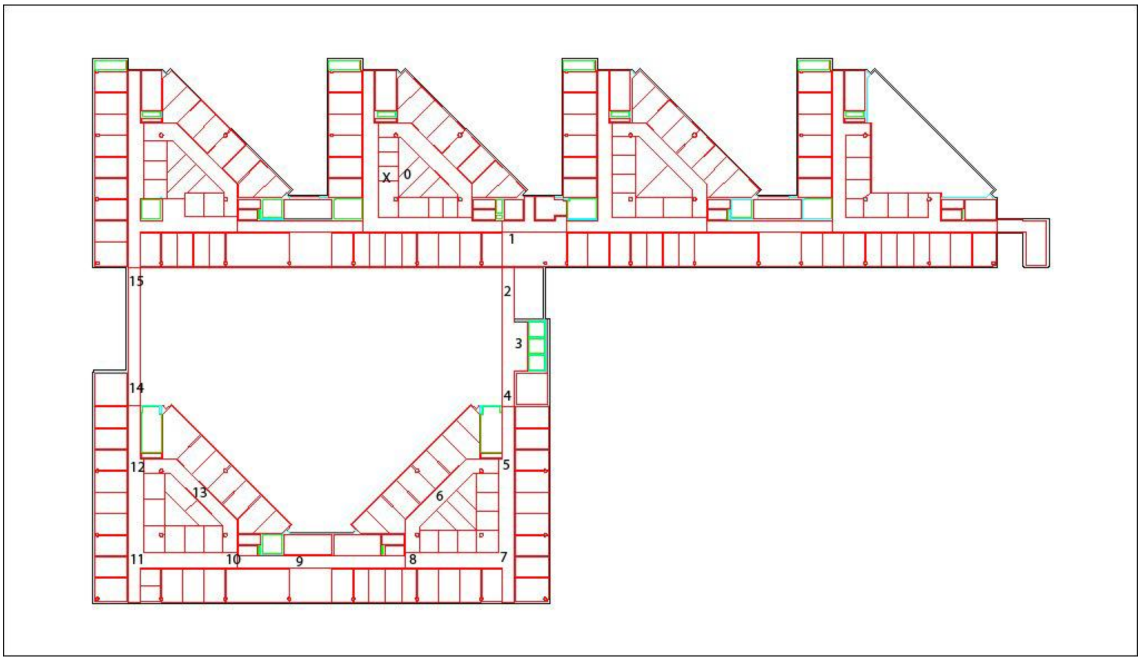

Figure 30. NRC 3rd floor measurement points.

In total 15 measurement points were visited on the third floor. Due to restrictions in access, no larger coverage at this floor was possible. As with fourth floor, elevator shafts and stairwells are marked with a greenish cyan color on the floor plan. The triangular area in the middle of each wing was an open office area. The rooms were separated from the corridors with glass walls. Figures 31 and 32 display the relative attenuation figures for both connections.

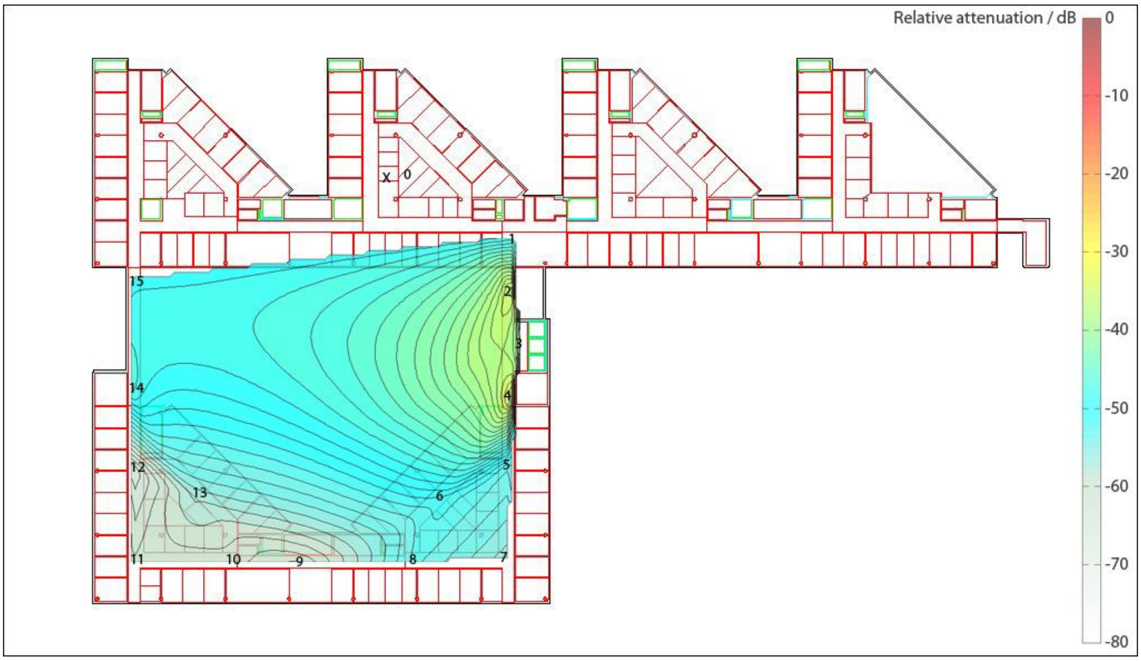

Figure 31. NRC 3rd floor white space device relative attenuation.

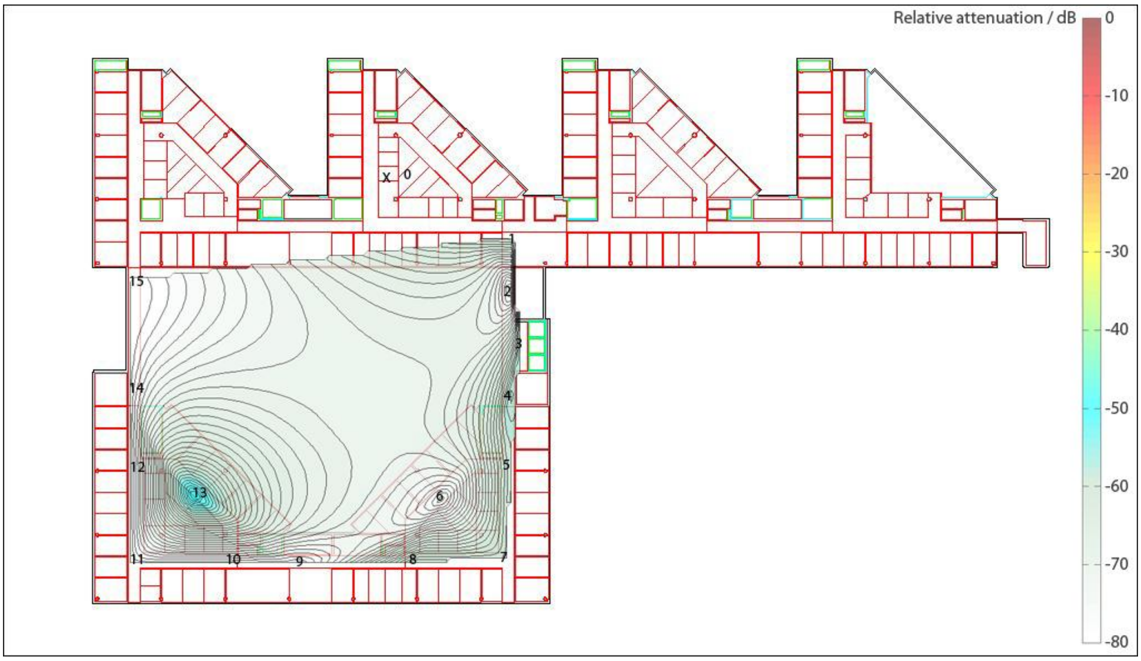

Figure 32. NRC 3rd floor WLAN relative attenuation.

Attenuation figures display the same behavior as on the fourth floor, the relative attenuation seems lower for the WSD. This can further be seen in Figure 33 displaying the relative attenuation difference of the connections.

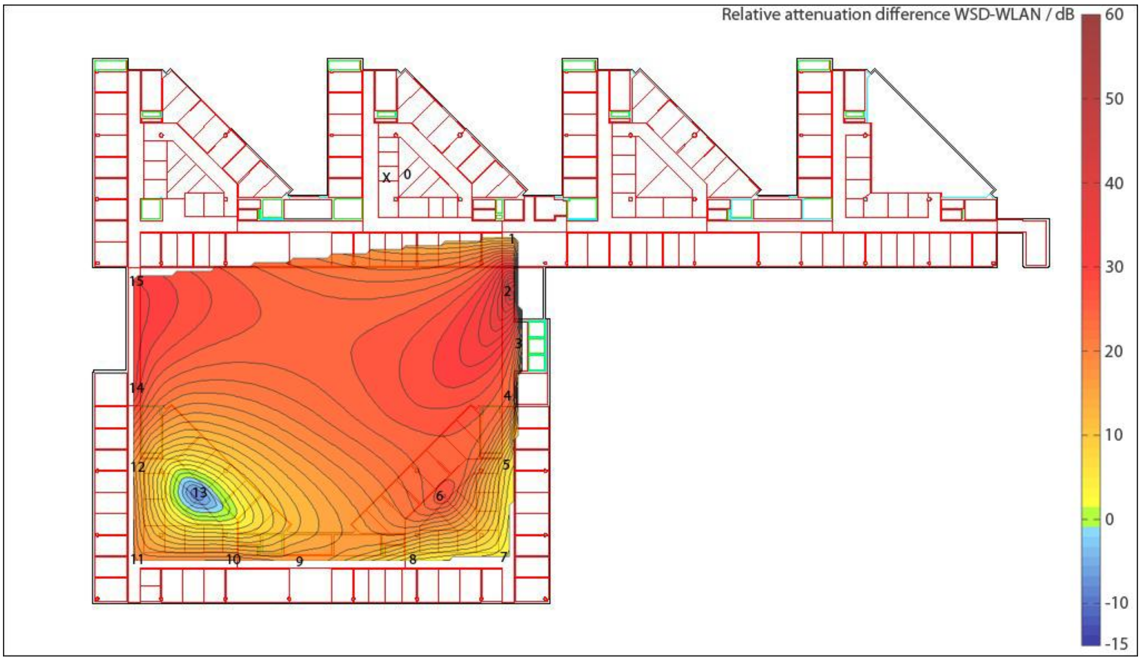

Figure 33. NRC 3rd floor relative attenuation difference.

In eight of the measurement locations no WLAN signal was detected in any of the five measurements. Additionally in several locations two or more measurements yielded no WLAN detection. Only in one measurement location the WLAN reception was stronger, and even there two of the measurements did not provide detection. Interference from many WLAN access points in the area was apparent. WSD connection with internet browsing was successful in all measurement locations. Attenuation differences as high as 46 dB were calculated.

4.1.3 Second Floor

Figure 34 displays the measurement points on the second floor at NRC. Included are also X and 0 marking the location of the transmitters and reference measurement point respectively on the fourth floor. A total of 14 measurement points were visited, restricted access limiting the measurements on this floor as well.

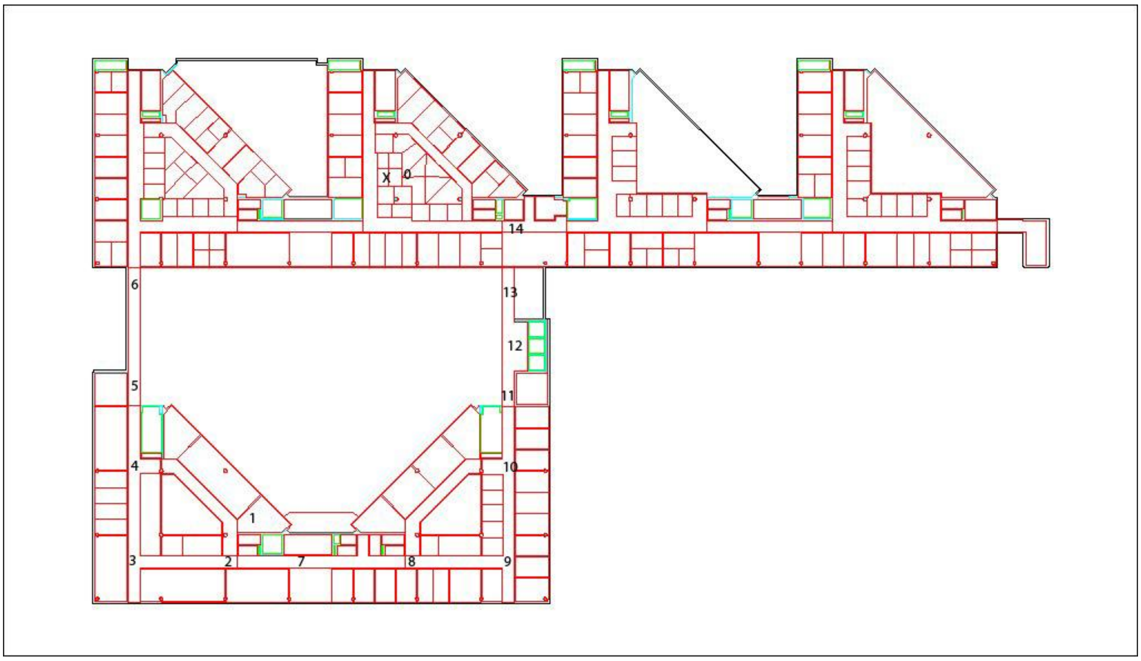

Figure 34. NRC 2nd floor measurement points.

As with previous floors, elevator shafts and stairwells are marked with a greenish cyan color on the floor plan. The triangular area in the middle of each wing was an open office area where as the triangles at the bottom part of the figure were conference rooms. Rooms were separated from the corridors with glass walls. Figures 35 and 36 display the attenuation measurements for both connections.

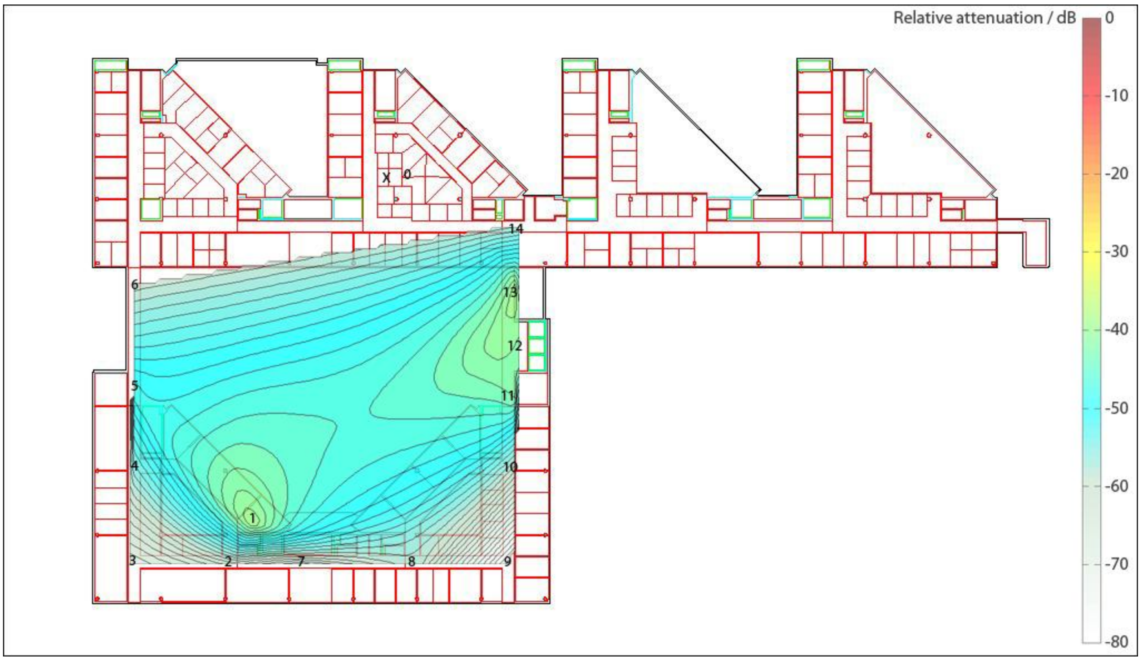

Figure 35. NRC 2nd floor white space device relative attenuation.

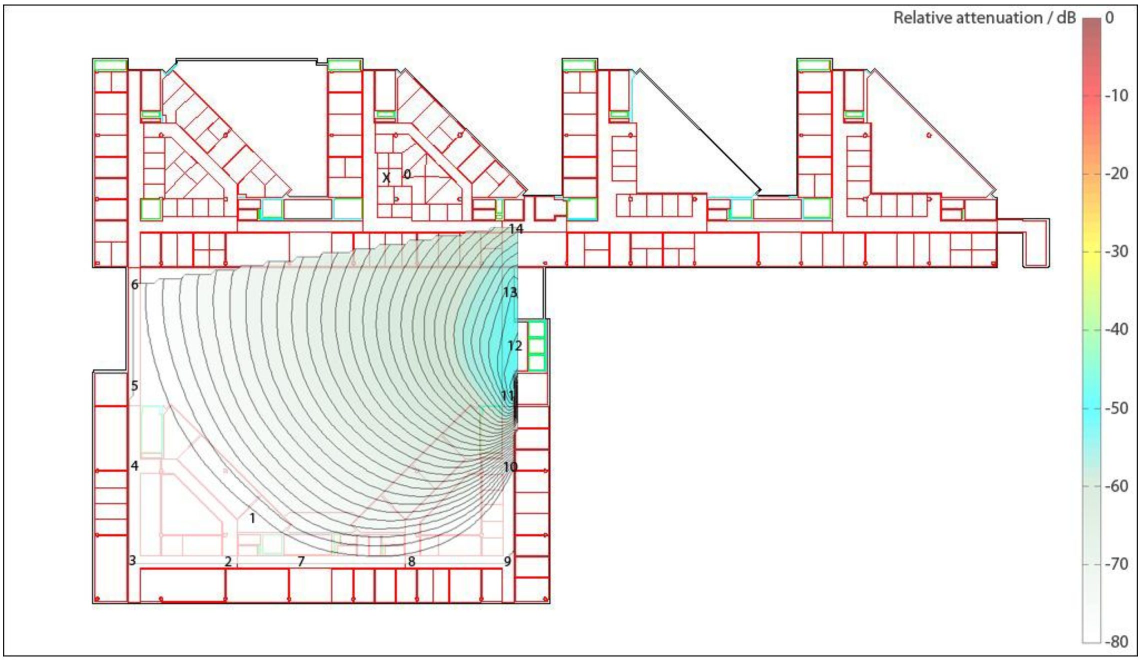

Figure 36. NRC 2nd floor WLAN relative attenuation.

The trend in the two upper floors continues on the second floor. Attenuation of the WLAN connection appears greater. Figure 37 displays the relative attenuation difference of the connections.

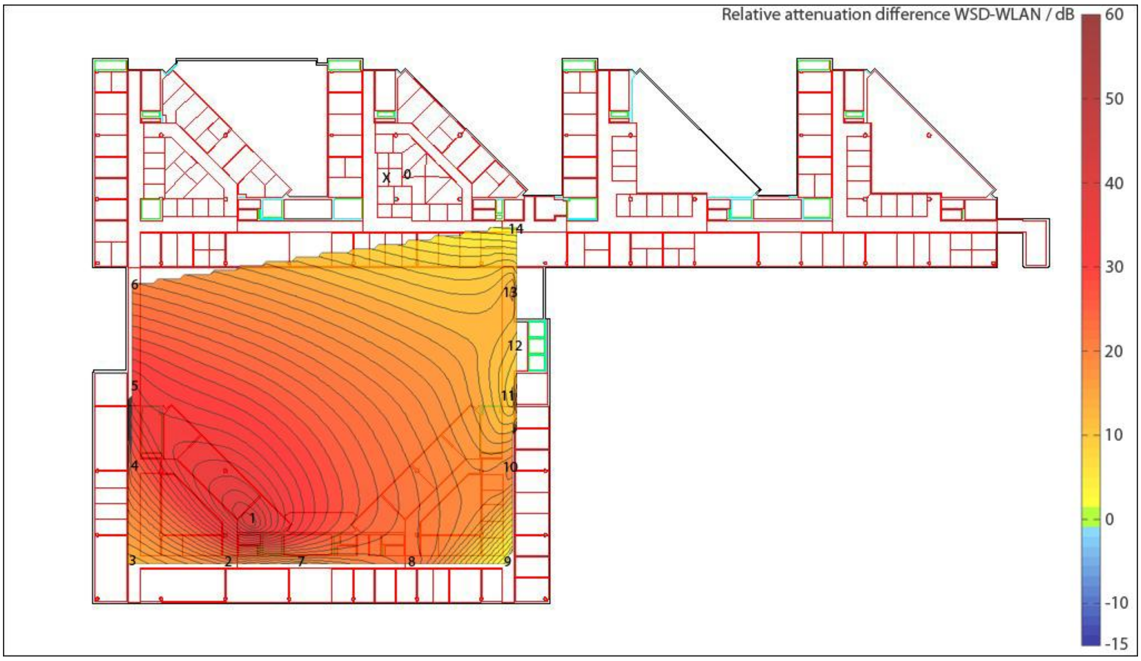

Figure 37. NRC 2nd floor relative attenuation difference.

Out of 14 measurement points 10 yielded no WLAN detection. However, the interfering WLANs were likely to have at least some role in this. Only in both lower corners the WSD failed to get the signal properly, in 9 out of 10 measurements it failed to get a connection. Internet browsing with the WSD connection was possible in all but these two locations. Even as high as 40 dB attenuation differences were calculated.

4.1.4 First floor

Figure 38 displays the measurement points on the first floor at NRC. Included are also X and 0 marking the location of the transmitters and reference measurement point respectively in the fourth floor. A total of 14 measurement points were visited.

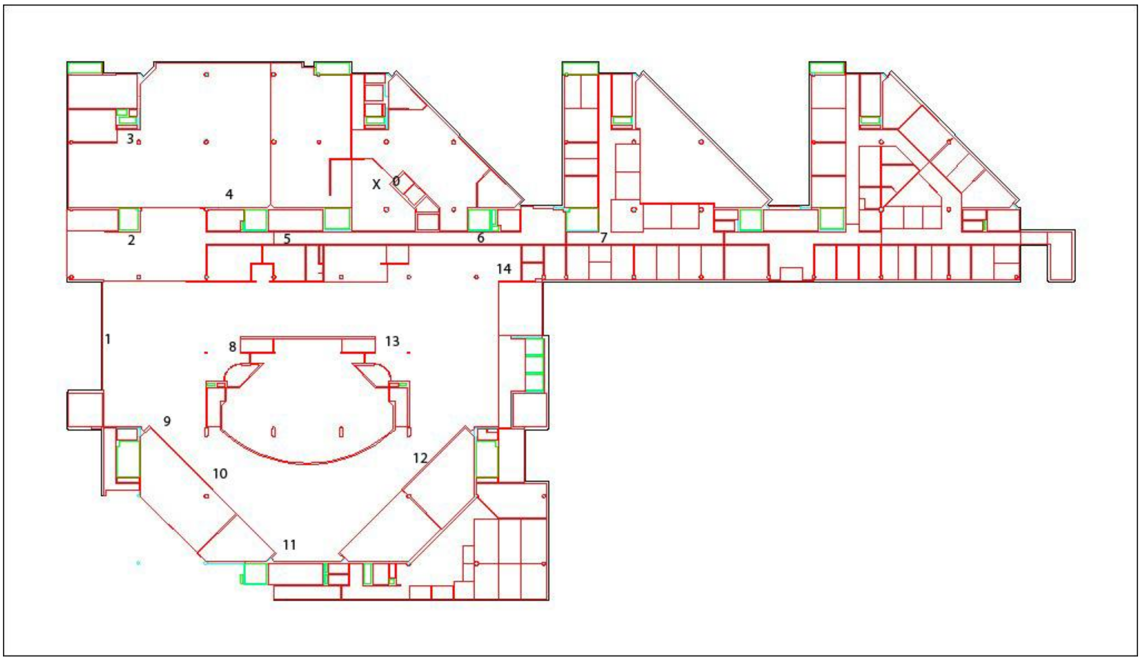

Figure 38. NRC 1st floor measurement points.

As with the previous floors, elevator shafts and stairwells are marked with a greenish cyan color on the floor plan. The first floor differs from the other floors as there is a cafeteria and dining area adjacent to the lobby in the top left corner of the floor plan. Additionally, in the middle of the lobby there is a structure housing an auditorium. Figures 39 and 40 display the attenuation measurement results for the connections.

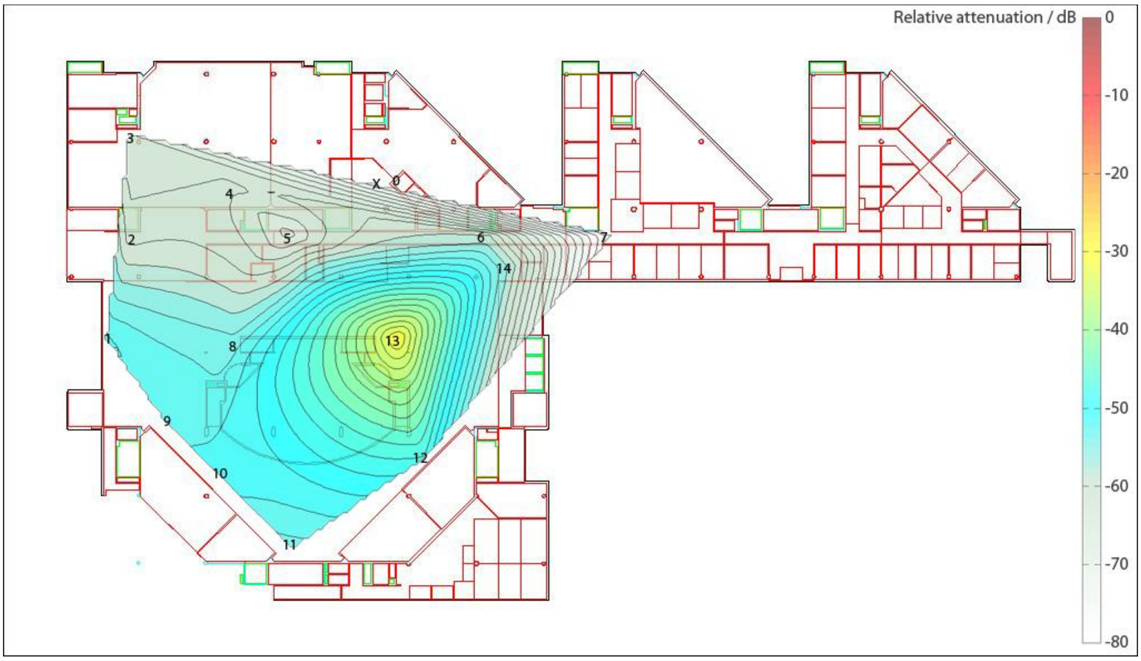

Figure 39. NRC 1st floor white space device relative attenuation.

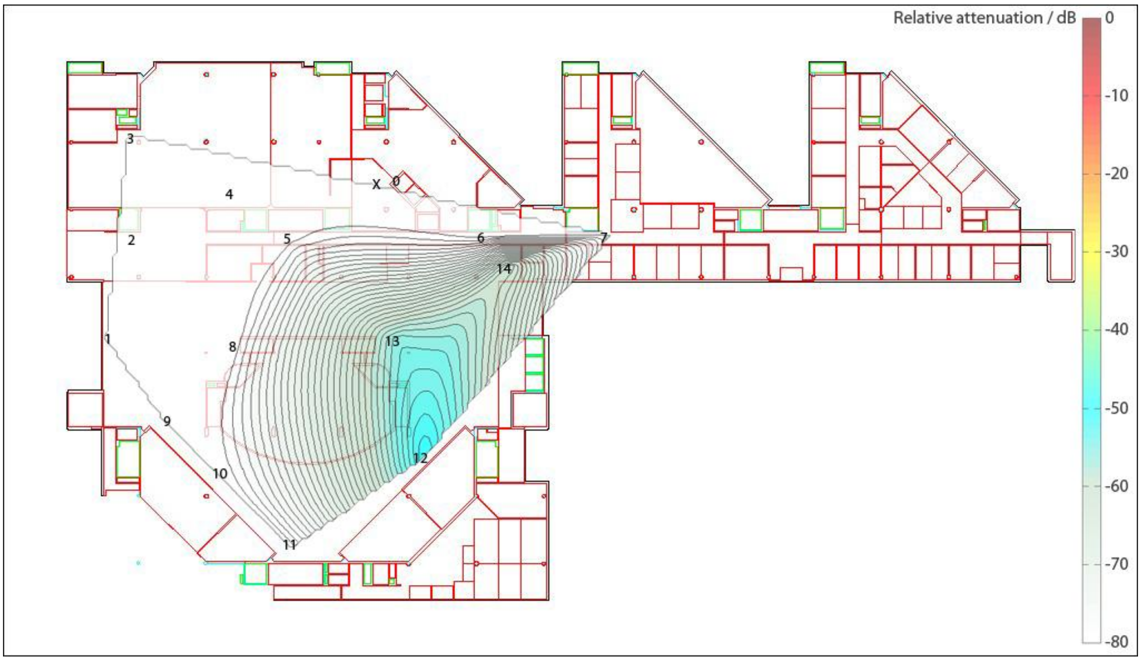

Figure 40. NRC 1st floor WLAN relative attenuation.

Coverage in the lobby was markedly better for both connection types than on the second floor. This was mainly due to lobby being an open area. There also was a relatively unobstructed spot in relation to the transmitters where both connections reached their peak reception on the first floor. Figure 41 displays the relative attenuation difference for the connections.

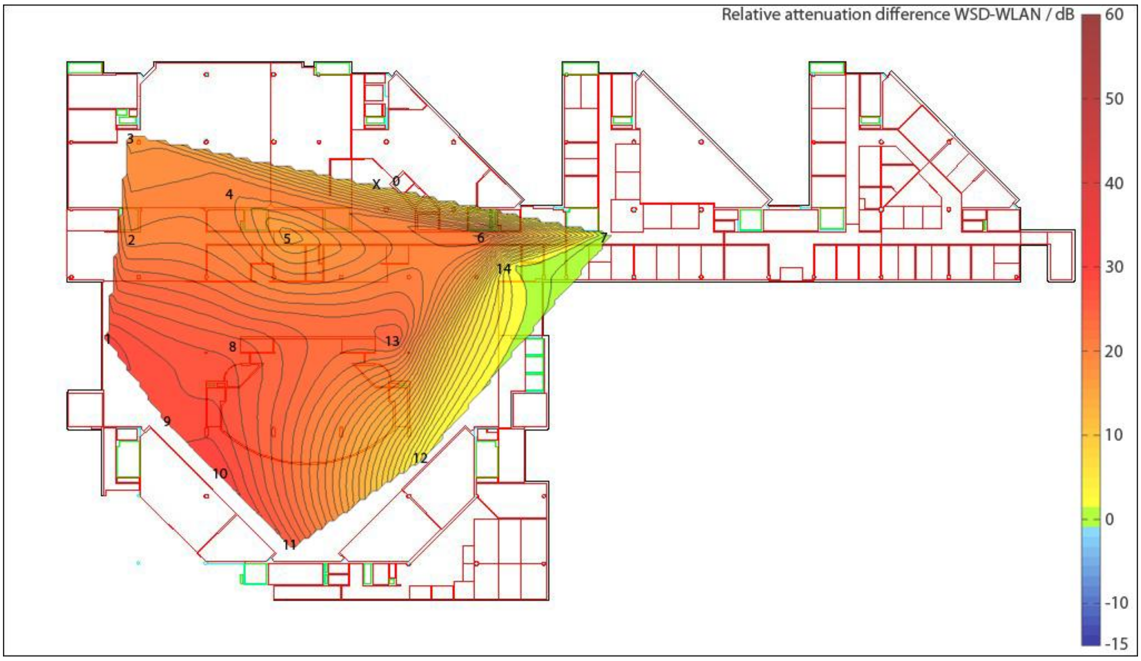

Figure 41. NRC 1st floor relative attenuation difference.

WLAN coverage was again weaker with 11 out of 14 measurement locations providing no connection in any of the measurements. As ever, the presence of interference from the numerous WLAN access points in the area must have partly contributed to this. Measurement point 7 at the far right was the only one with no connectivity for the WSD. In all other locations internet browsing was possible, albeit slow in some cases. Attenuation differences as high as 29 dB in favor of the WSD were calculated.

Following section discusses the measurements conducted at the Digita offices.

4.2 Digita

The measurements at Digita offices were conducted over several days assisted and supervised by a Digita representative.

The outer walls of the building are constructed of bricks. One side of the building has office rooms with light plaster walls on it and the on other side there is an open office area with cubicles. In addition to the outer walls, heavier load bearing walls can also be found around elevator shafts and staircases.

As free access to the internet was provided with a high speed connection, also a connection speed test was done at each measurement point when the connection was available. Both downlink and uplink throughput tests were conducted and the values recorded and plotted. Speed test used was provided by www.speedtest.net. The closest server in Finland was used for the test.

The value -60 dBm, which could in reality have been anything from -60 dBm to -75 dBm, featured in sixteen of the sixth floor, five of the fifth floor and one of the third floor measurement points. In seven of the sixth floor, one of the fifth floor and one of the third floor measurement points only one value of the five recorded at each point was compromised. That value was excluded from the calculation of the average RSSI for that location. When the number of compromised measurements was greater than one, the RSSI values were plotted with both the actual measured values and values based on estimation according to surrounding values and attenuation increase in other floors at the same location.

Reference values closest to the transmitters in fourth floor at Digita were -23,2 dBm for the white space device and -29,8 dBm for the WLAN.

The data recorded during the measurements at Digita offices is included in the Appendix 3.

4.2.1 Sixth Floor

The transmitters were placed on the sixth floor of the Digita offices. The location of the transmitters is marked with an X in Figure 42. All measurement points on the sixth floor are also numbered in the figure. A total of 45 measurement locations were visited on the sixth floor.

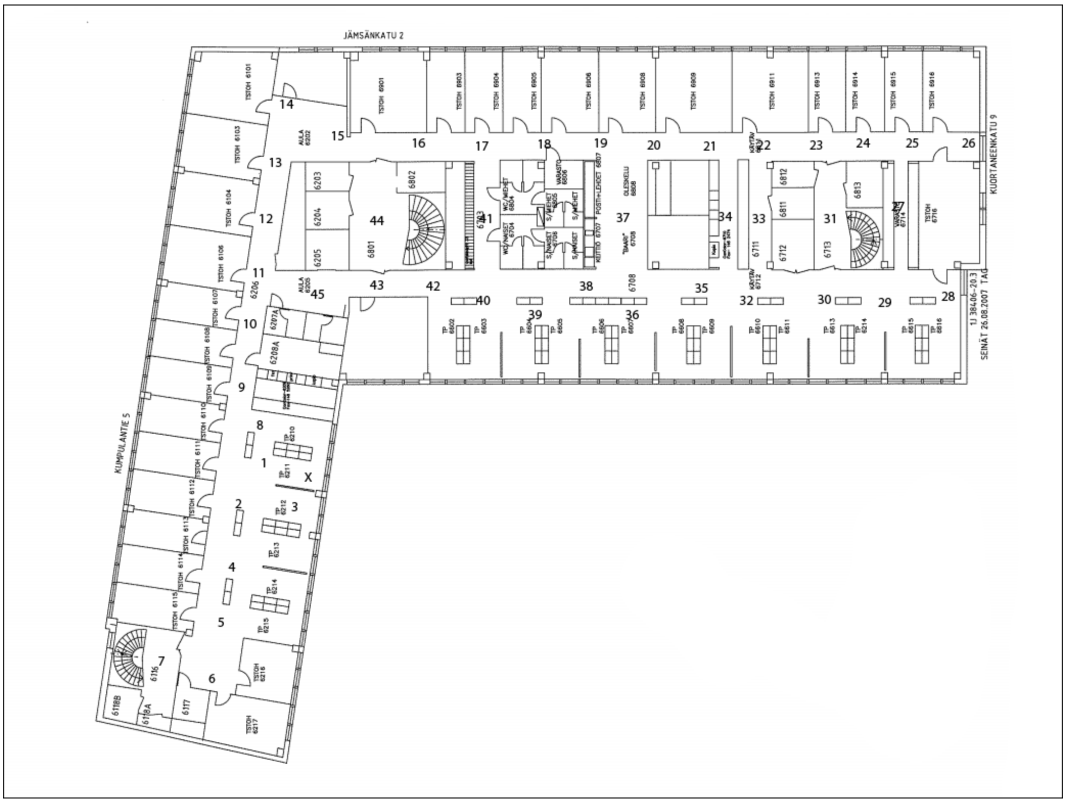

Figure 42. Digita offices 6th floor measurement points.

The office rooms can be seen along the left and top walls of the building. Along the right and bottom wall were the open areas with cubicles. The formations constructed of small squares were roughly 1,5 meter high cabinets.

Figures 43 to 45 display the relative attenuation for both connections. For WSD connection two versions are presented.

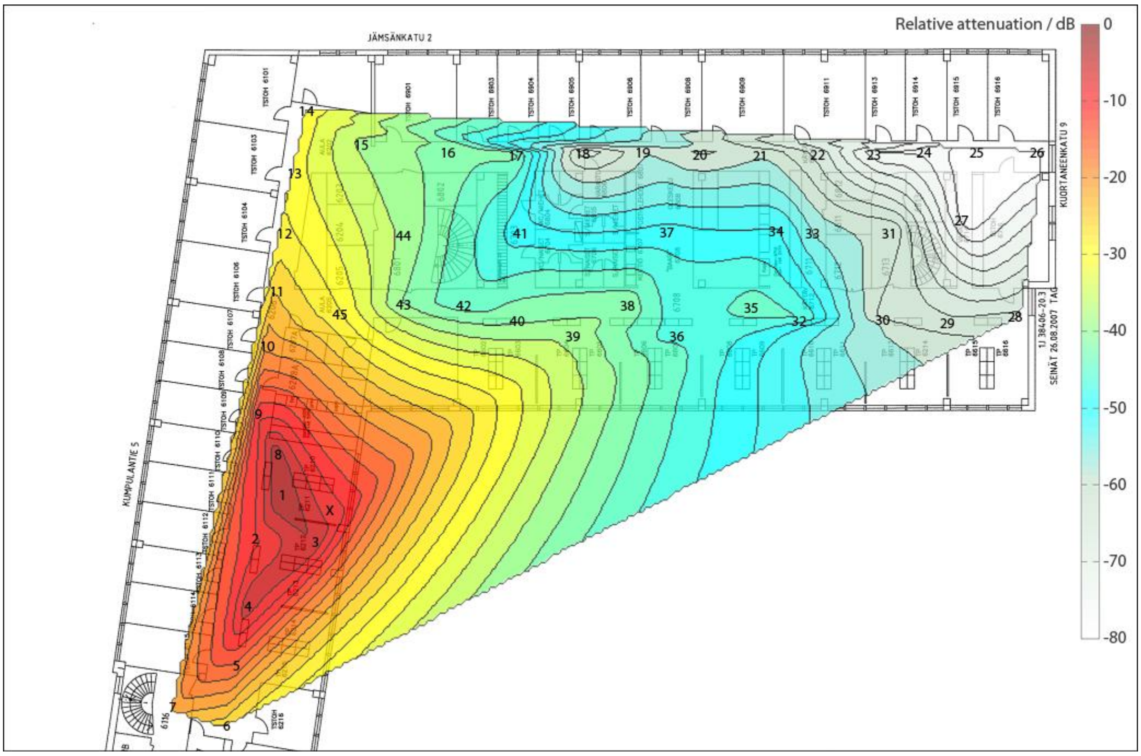

Figure 43. Digita offices 6th floor white space device relative attenuation.

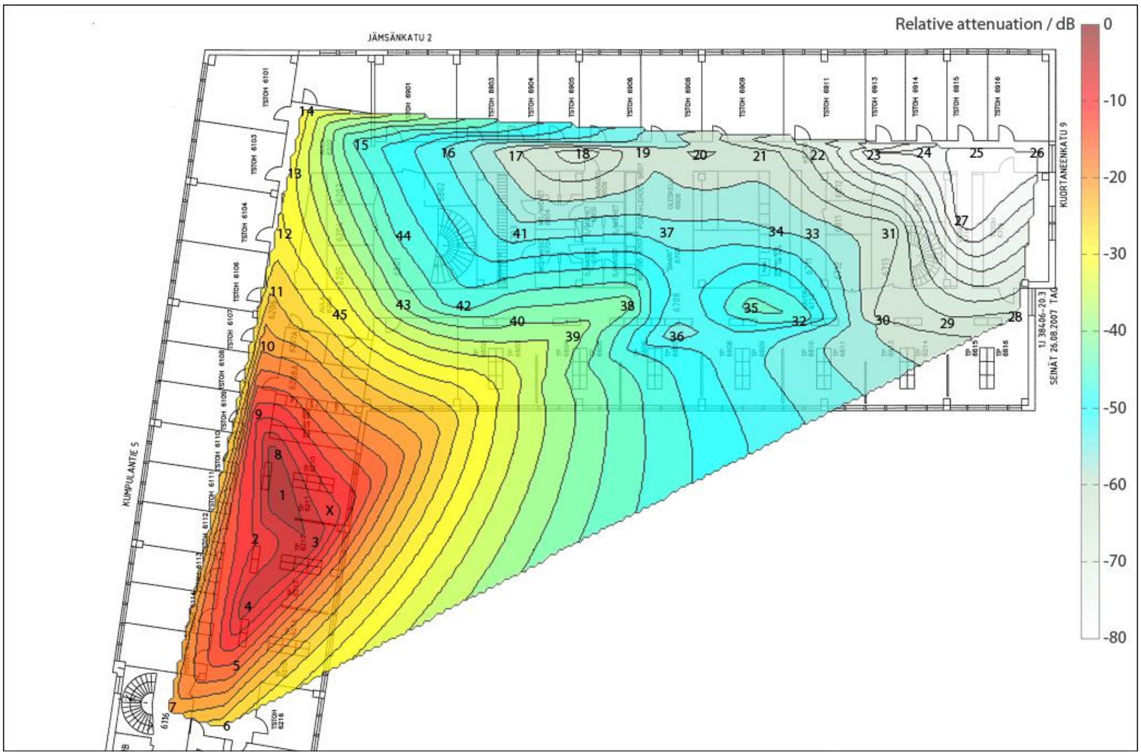

Figure 44. Digita offices 6th floor white space device relative attenuation, modified.

From measurement point 15 to 17 the TVBD Element Manager provided almost a flat result of -60 dBm. Also in measurement point 44 in the same area the measurement readings were all -60 dBm. In measurement points 34, 36, 37 41 and 42 two or three measurements provided this result as well. As mentioned before, the measurements were corrected based on the results at the closest measurement points with reliable data. The effect of the approximation is clearly visible in the plots, especially in the upper left corner where the values of three consecutive points had to be lowered with as much as 6 to 12 dB.

In three measurement points in the top right corner no WSD connection was possible.

Figure 45 displays the relative attenuation for the WLAN connection.

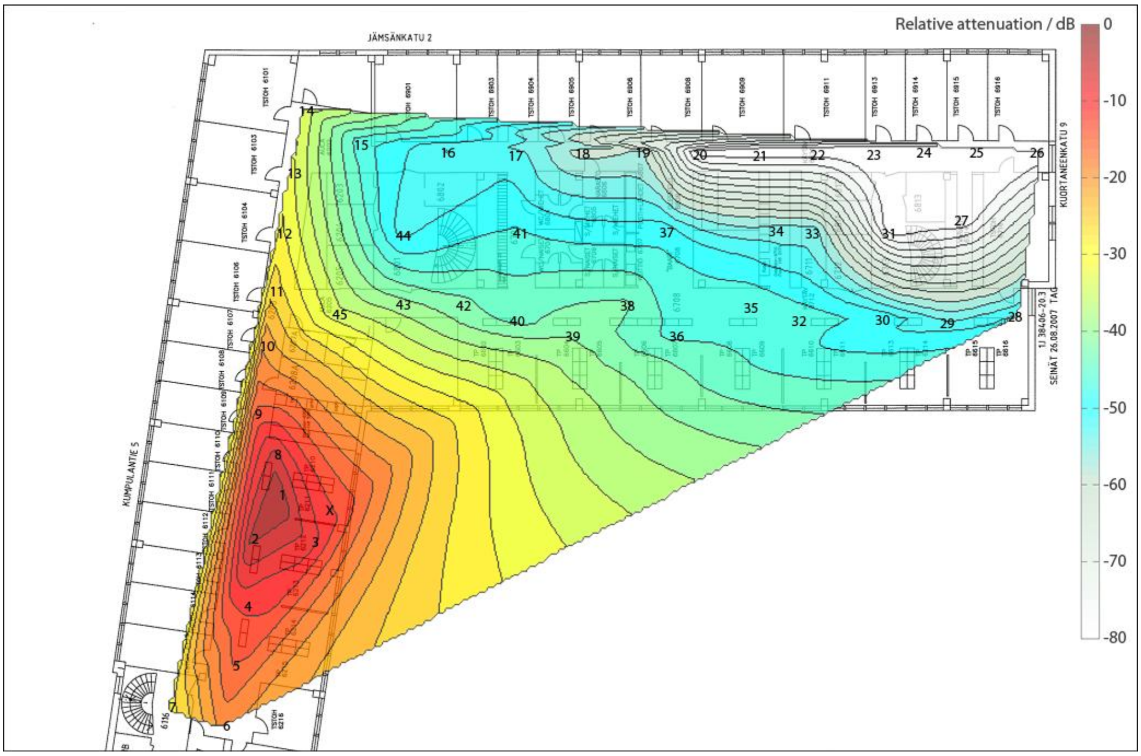

Figure 45. Digita offices 6th floor WLAN relative attenuation.

In the top right corner also WLAN adapter failed to make a connection. In total nine out of 45 measurement locations provided no WLAN coverage.

Figures 46 and 47 display the difference between the two signals as coverage maps. The difference is counted for both the raw and modified data.

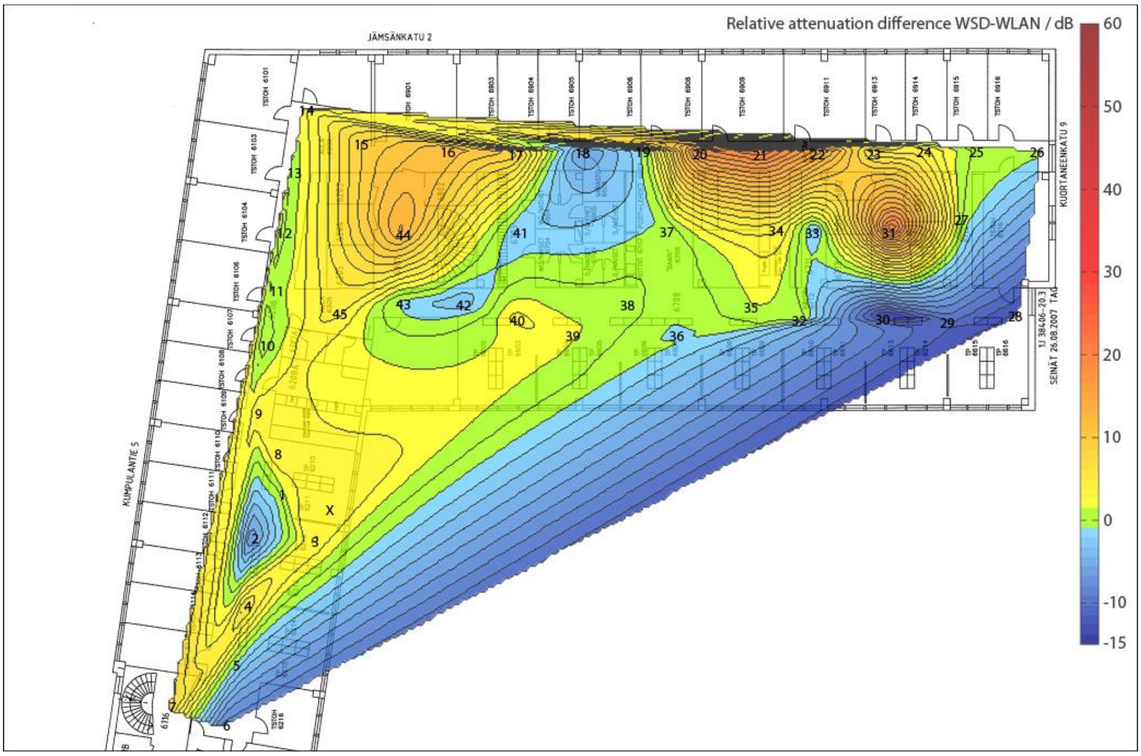

Figure 46. Digita offices 6th floor relative attenuation difference.

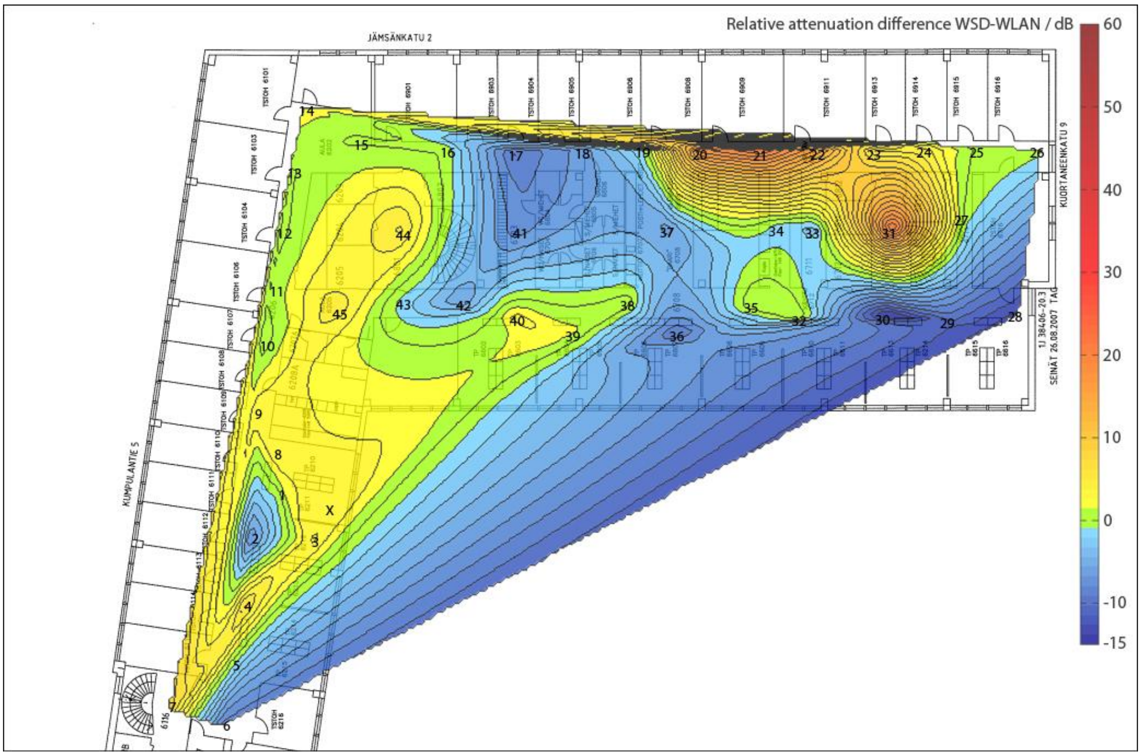

Figure 47. Digita offices 6th floor relative attenuation difference, modified.

Colors from red to yellow indicate locations with less attenuation on the WSD connection, green indicates roughly equal attenuation and shades of blue indicate less attenuation on the WLAN connection.

As there were less than 10 active WLAN access points in the range, WLAN measurements at the Digita offices were not as compromised as those carried out at the Nokia Research Center. As even as low received power levels as -84 dBm were recorded for the WLAN connection, the disturbing interference could be rather safely ruled out. The results of measurement data modification are clearly visible in all locations where the modification was needed, i.e. the blue color indicating WLAN dominance spreading. As there is no way of telling how correct the modifications were, the results should be considered merely guiding.

In top right corner the WSD provides better results than WLAN. Notable is that WSD dominance is at the strongest at the farthest reach of the signal where WLAN could not reach. In addition, this corner also was behind a block of heavier walls housing an elevator shaft and a stairwell.

Figures 48 and 49 display the downlink and uplink throughput of the WSD connection.

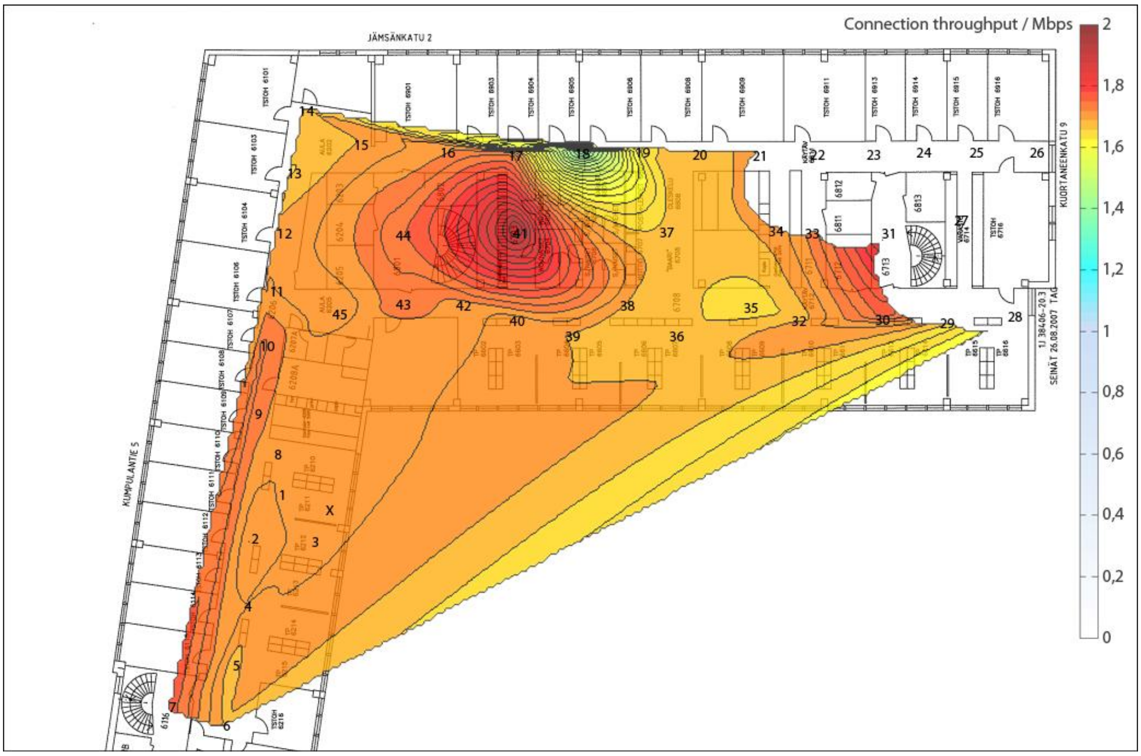

Figure 48. Digita offices 6th floor WSD downlink throughput.

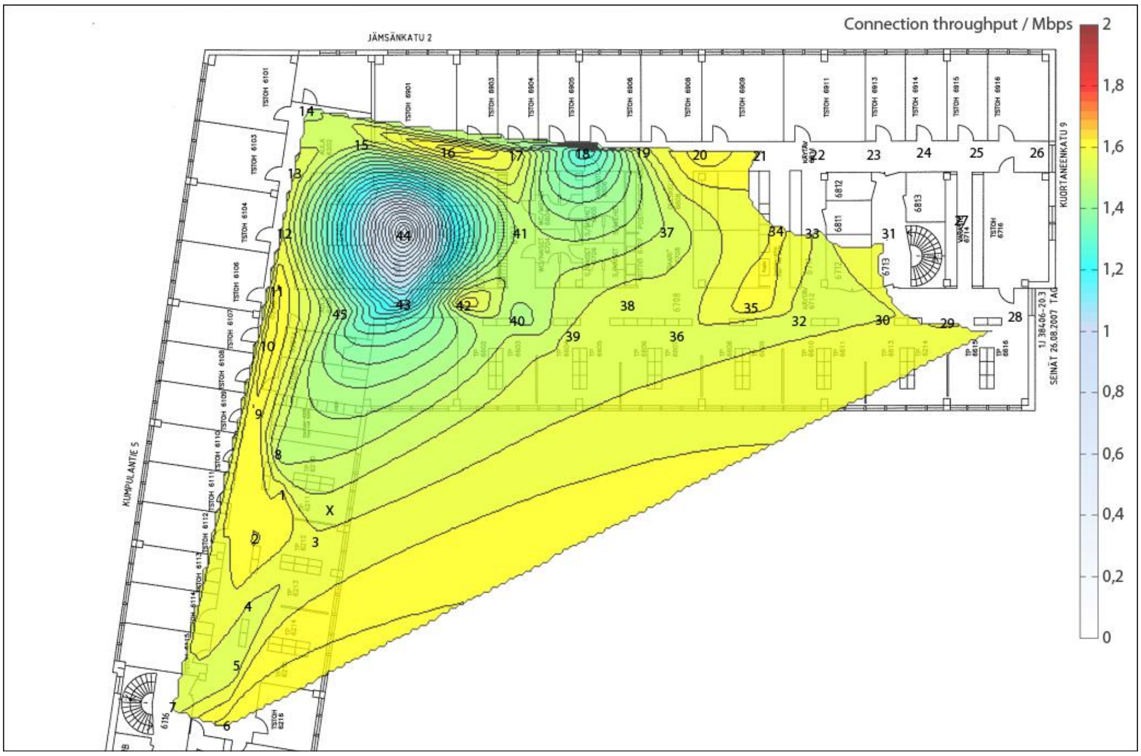

Figure 49. Digita offices 6th floor WSD uplink throughput.

The performance of the WSD connection was rather stable. Almost everywhere the connection was possible, the variation in speed was relatively small. The major peaks and dips seen in the figures were caused by issues connecting to the test server. The latency or response time of the server was markedly higher during measurements in these locations. As the normal latency was around 10 ms, even as high as 1,5 s latencies were measured. Due to the high latency the test finished faster as the size of the test packet was decreased by the server.

4.2.2 Fifth Floor

Figure 50 displays the measurement points on the fifth floor at Digita offices. Included are also X and 0 marking the location of the transmitters and reference measurement point respectively on the sixth floor. A total of 18 measurement points were visited on the fifth floor.

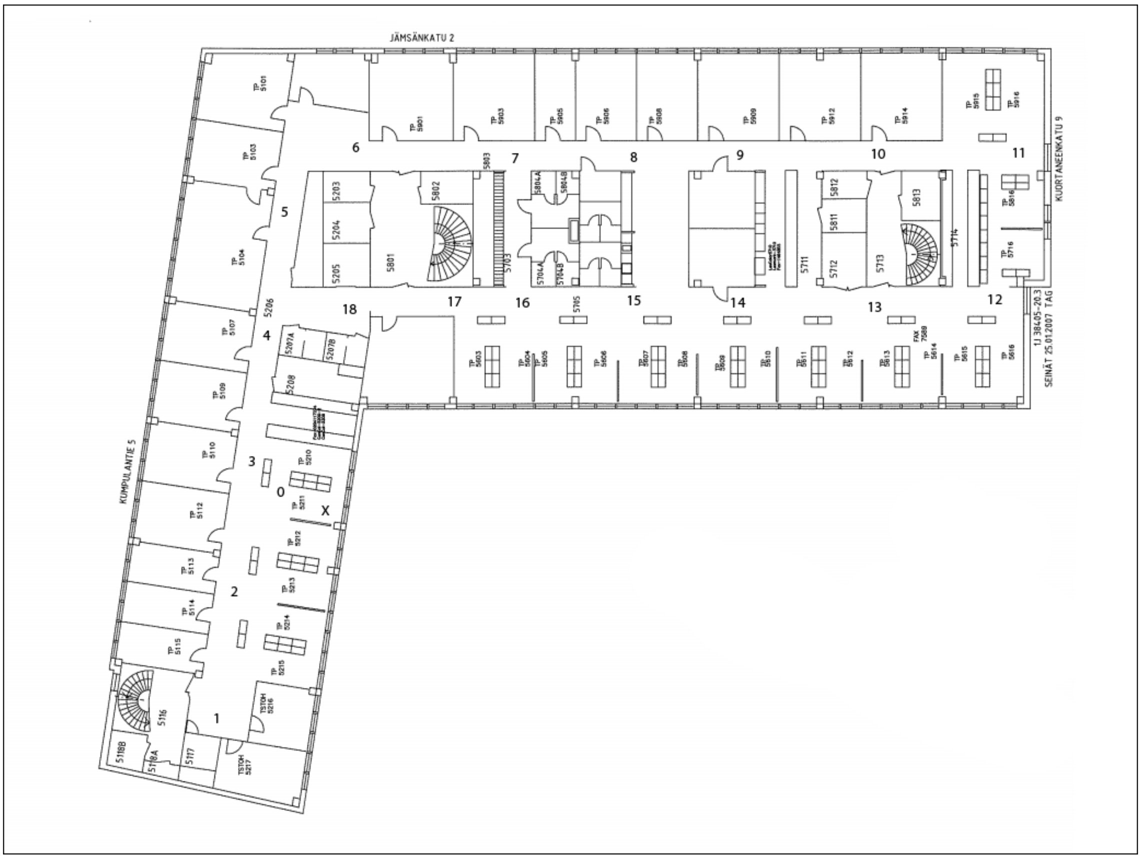

Figure 50. Digita offices 5th floor measurement points.

The office rooms can be seen along the left and top walls of the building. Along the right and bottom wall were the open areas with cubicles. The formations constructed of small squares were roughly 1,5 meter high cabinets.

Figures 51 to 53 display the relative attenuation for both connections. For WSD connection two versions are presented.

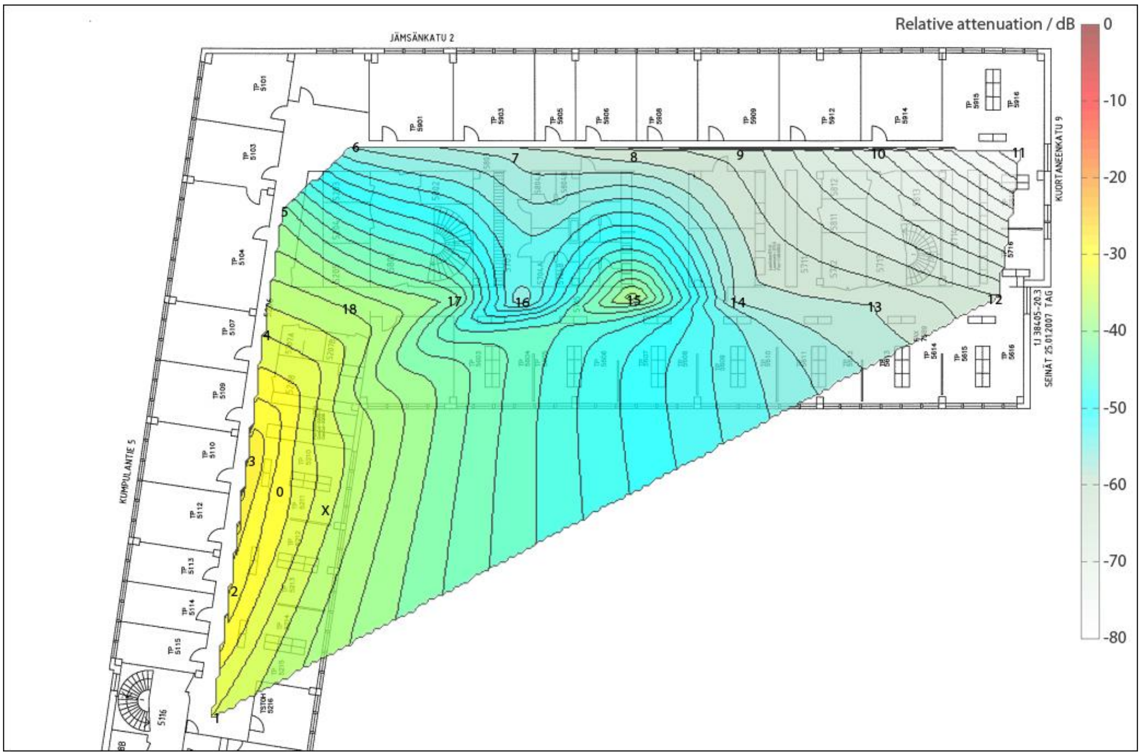

Figure 51. Digita offices 5th floor white space device relative attenuation.

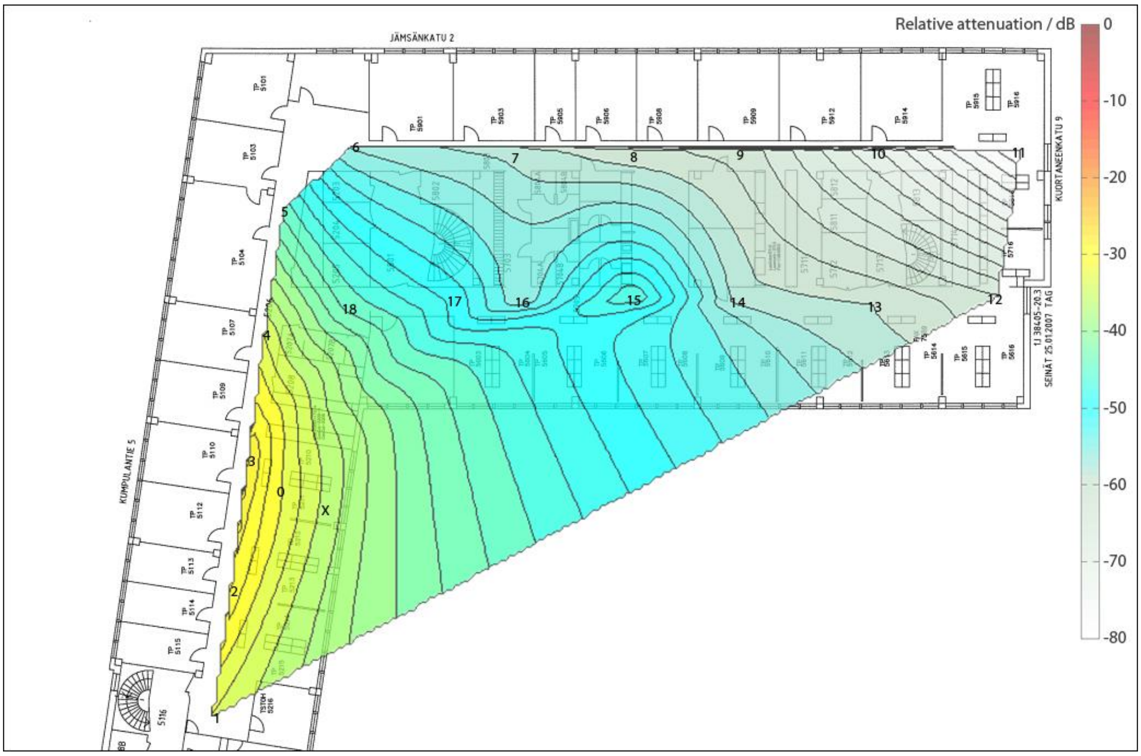

Figure 52. Digita offices 5th floor white space device relative attenuation, modified.

At each of the measurement points 5, 17 and 18 three to four measurements yielded the result -60 dBm. In measurement point 15 all measurements provided this result. Based on the reliable results from the sixth floor and neighboring results on the fifth floor, an estimation was done to make the results more truthful. As much as 8 dB attenuation was added in measurement point 15. Only in measurement point 11 there was no WSD connection available.

Figure 53 displays the relative attenuation of the WLAN connection.

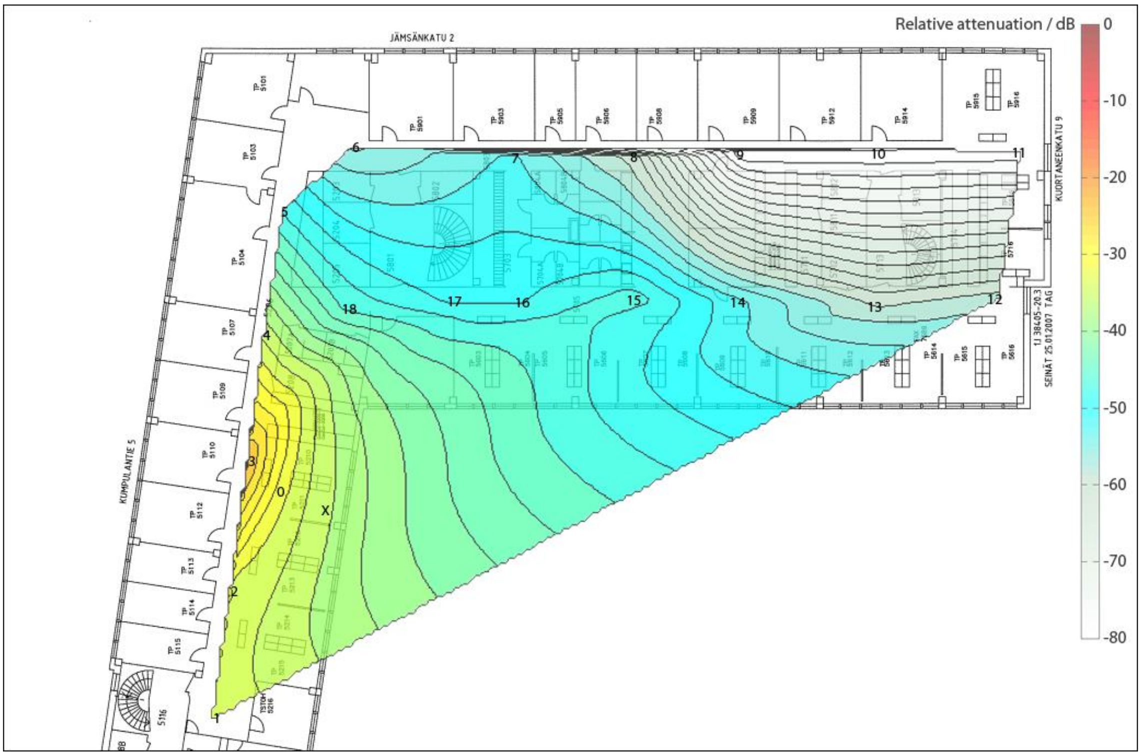

Figure 53. Digita offices 5th floor WLAN relative attenuation.

The WLAN connection was not available in any of the five measurements at measurement points 9, 10 and 11. In five of the remaining fifteen measurement points one to four of the five measurements provided no WLAN coverage.

Figures 54 and 55 show the relative attenuation differences between the two types of connection. As corrections to WSD results were needed, also the corrected difference figure is presented.

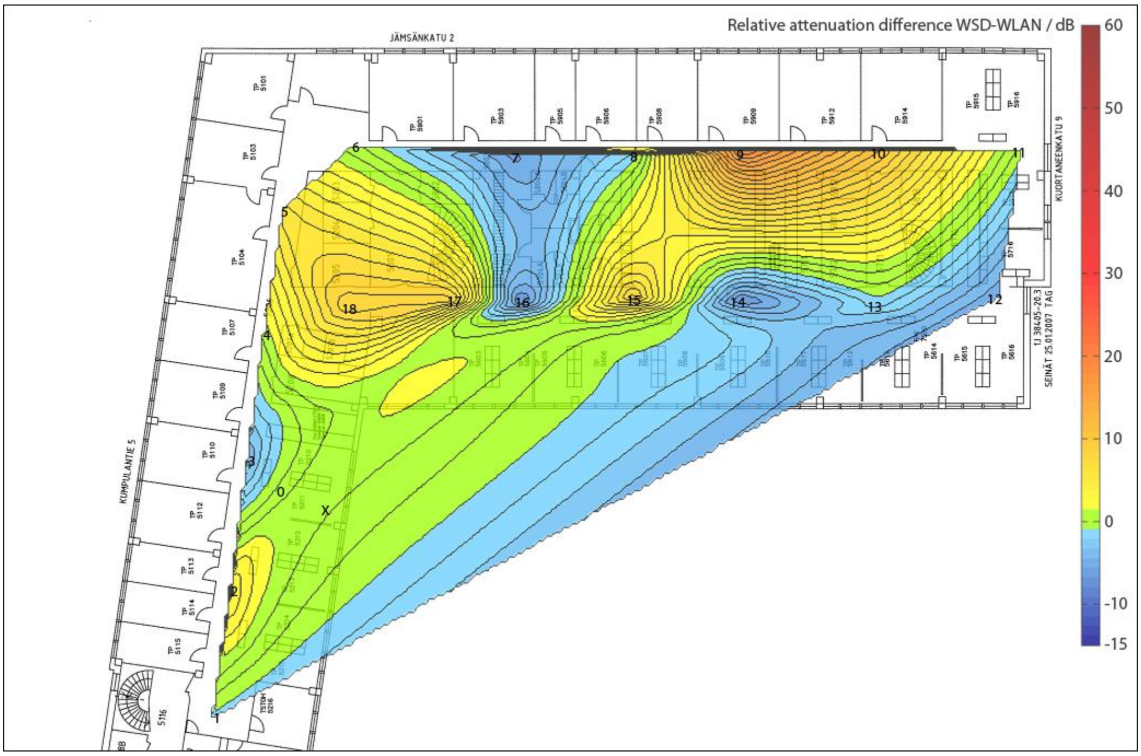

Figure 54. Digita offices 5th floor relative attenuation difference.

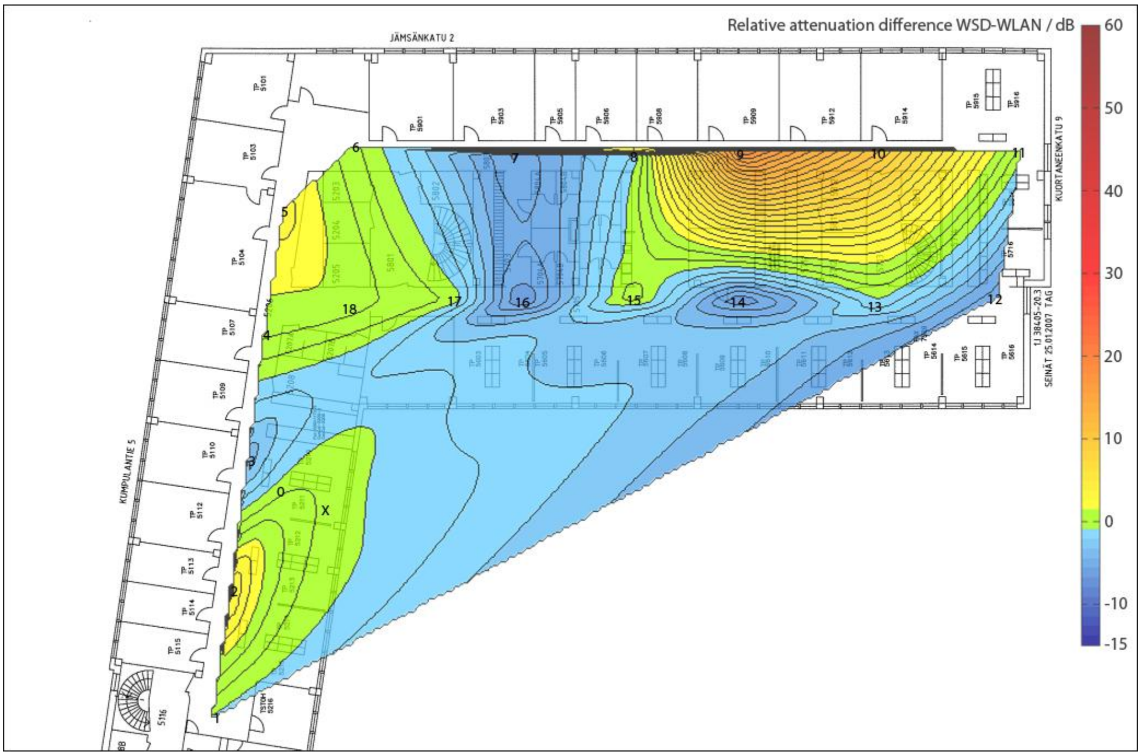

Figure 55. Digita offices 5th floor relative attenuation difference, modified.

Colors from red to yellow indicate locations with less attenuation on the WSD connection, green indicates roughly equal attenuation and shades of blue indicate less attenuation on the WLAN connection.

As general WLAN activity was lower, WLAN measurements at the Digita offices were not as compromised as those done at the Nokia Research Center. As even as low received power levels as -84 dBm were recorded for the WLAN connection, the disturbance could be rather safely ruled out. The results of WSD measurement data modification is clearly visible around measurement points 15, 17 and 18. The decrease of WSD dominance can be seen in clear reduction in the shades of yellow and increase in the shades of blue. As there is no way of telling how correct the modifications were, the results should be considered merely guiding.

As in the sixth floor, in top right corner the WSD provides better results than WLAN. Notable is that WSD dominance is at the strongest at the farthest reach of the signal where WLAN could not reach.

Figures 48 and 49 display the downlink and uplink throughput of the WSD connection.

Figure 56. Digita offices 5th floor WSD downlink throughput.

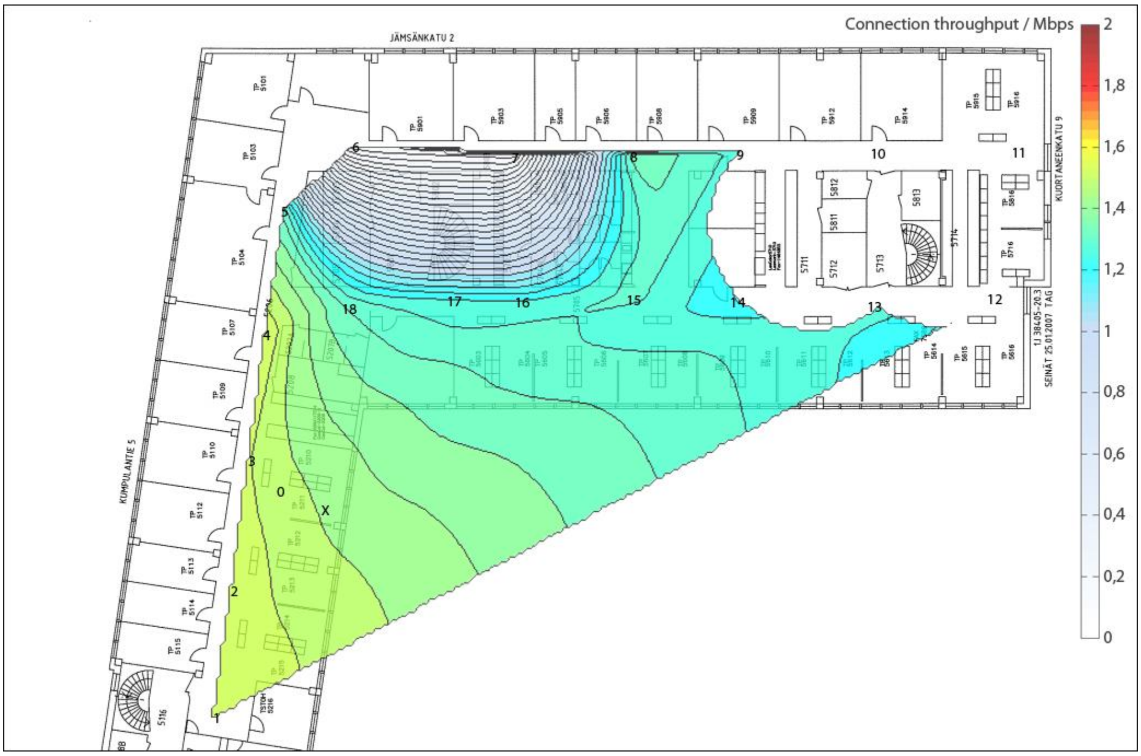

Figure 57. Digita offices 5th floor WSD uplink throughput.

The performance of the connection shows different behavior than in sixth floor. A clear decrease in both downlink and uplink throughput can be seen the farther away from the transmitters the receiver was moved. The major dips seen in the figures were caused by issues connecting to the test server. The latency or response time of the server was markedly higher during measurements in these locations, which affected the size of the test packet and made these results unreliable.

4.2.3 Third Floor

Figure 58 displays the measurement points on the third floor at Digita offices. Included are also X and 0 marking the location of the transmitters and reference measurement point respectively on the sixth floor. A total of 16 measurement points were visited on fifth floor.

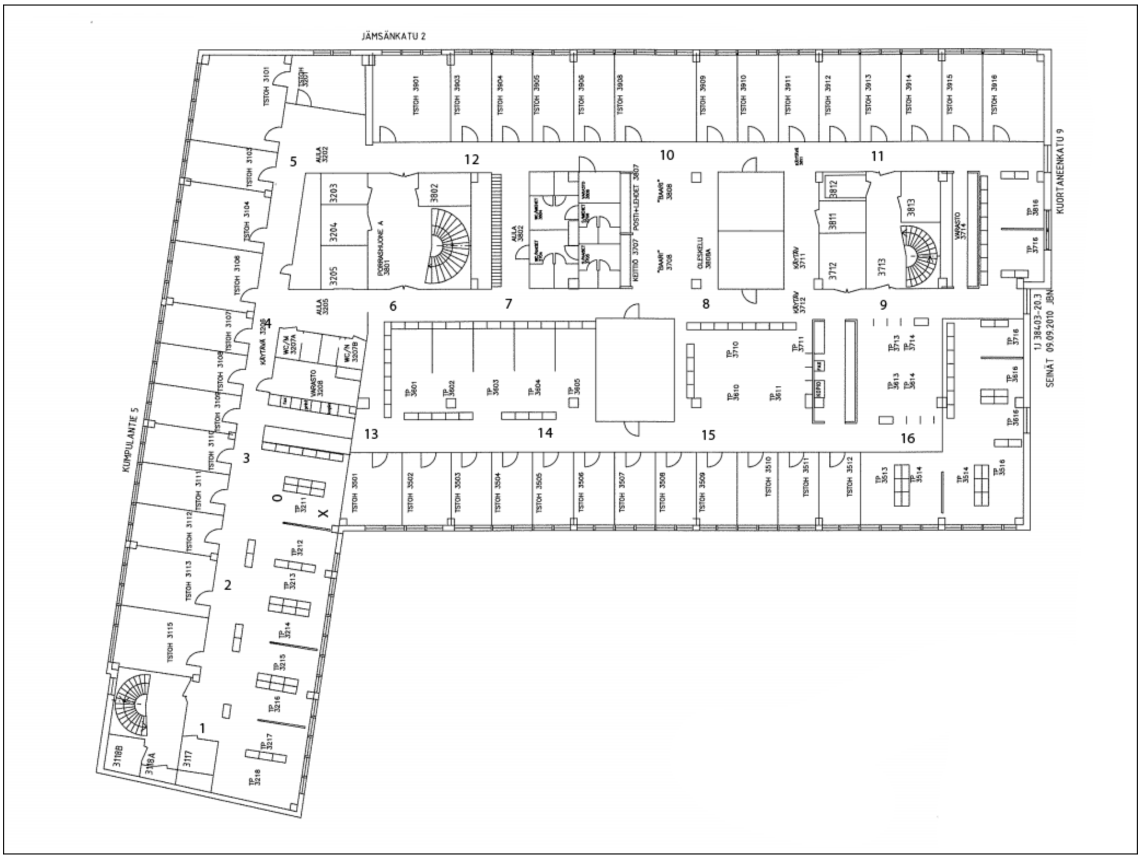

Figure 58. Digita offices 3rd floor measurement points.

The office rooms can be seen along the left, top and bottom walls of the building. Along the right wall and in the lower middle area of the horizontal part of the building were the open areas with cubicles. The formations constructed of small squares were roughly 1,5 meter high cabinets.

The horizontal section of the third floor at the Digita offices was larger than the floors above it. Lower part of this horizontal section was thus covered with a heavy outer roof instead of the ceiling between floors.

Figures 59 and 60 display the relative attenuation for both connections. As no measurement data modification was needed, only one figure per connection is shown.

Figure 59. Digita offices 3rd floor white space device relative attenuation.

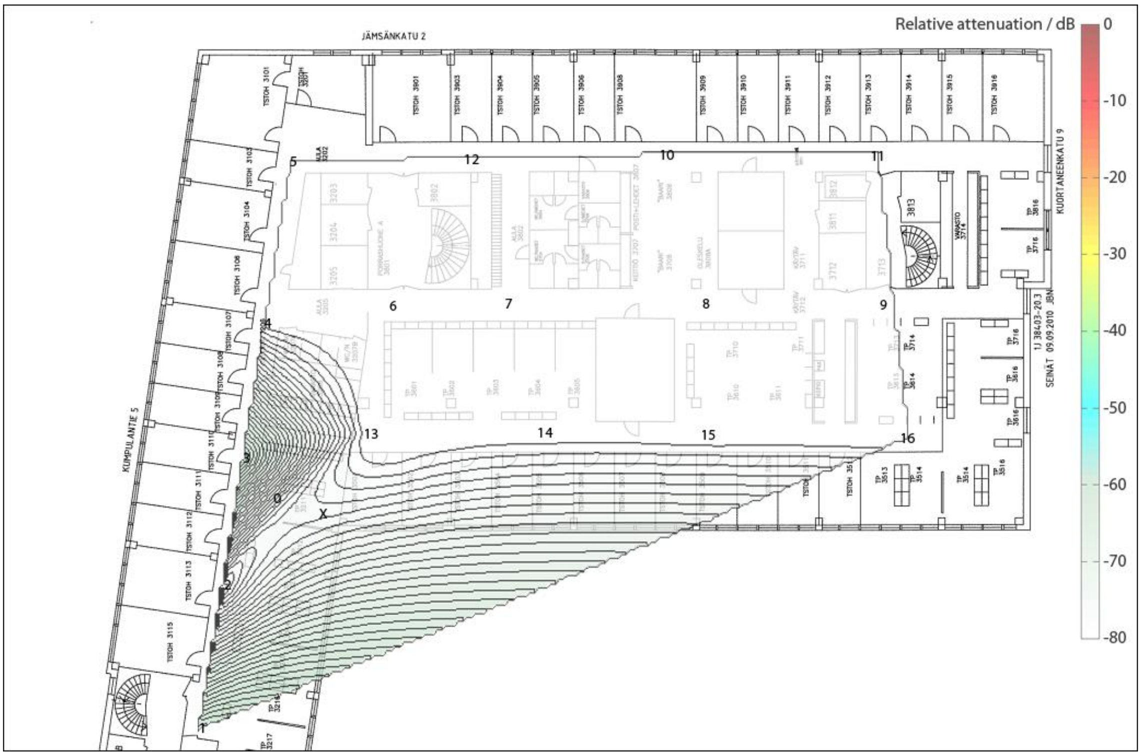

Figure 60. Digita offices 3rd floor WLAN relative attenuation.

No WSD connection was possible in measurement points 5, 11, 12, 15 and 16. Relative to the transmitter position, measurement points 5, 11 and 12 were behind heavy walls housing a stairwell and an elevator shaft. Points 15 and 16 were the most remote measurement points under the roof covering the lower part of the horizontal section of the building.

The WLAN connection was available only in measurement points 1 and 3. In all the other measurement points all five connection attempts failed.

Figure 61 shows the relative attenuation differences of the connections. As no measurement data modification was needed, only one figure is shown.

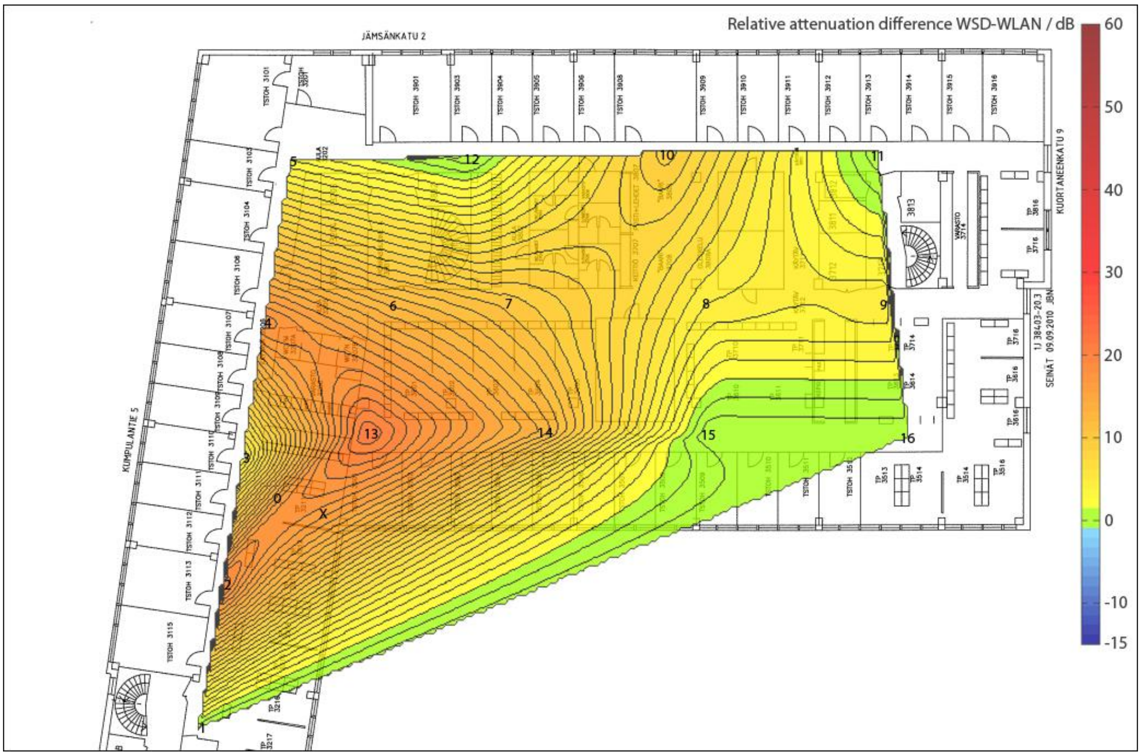

Figure 61. Digita offices 3rd floor relative attenuation difference.

As the WLAN coverage on the third floor was extremely limited, WSD dominance was to be expected. In no location did the WLAN reception surpass that of the WSD. Disturbance to the WLAN signal was limited as there was less than ten active WLAN access points in the area. As even as low received power levels as -83 dBm were recorded for the WLAN connection, the disturbance could be rather safely ruled out.

Figures 62 and 63 display the downlink and uplink throughput of the WSD connection.

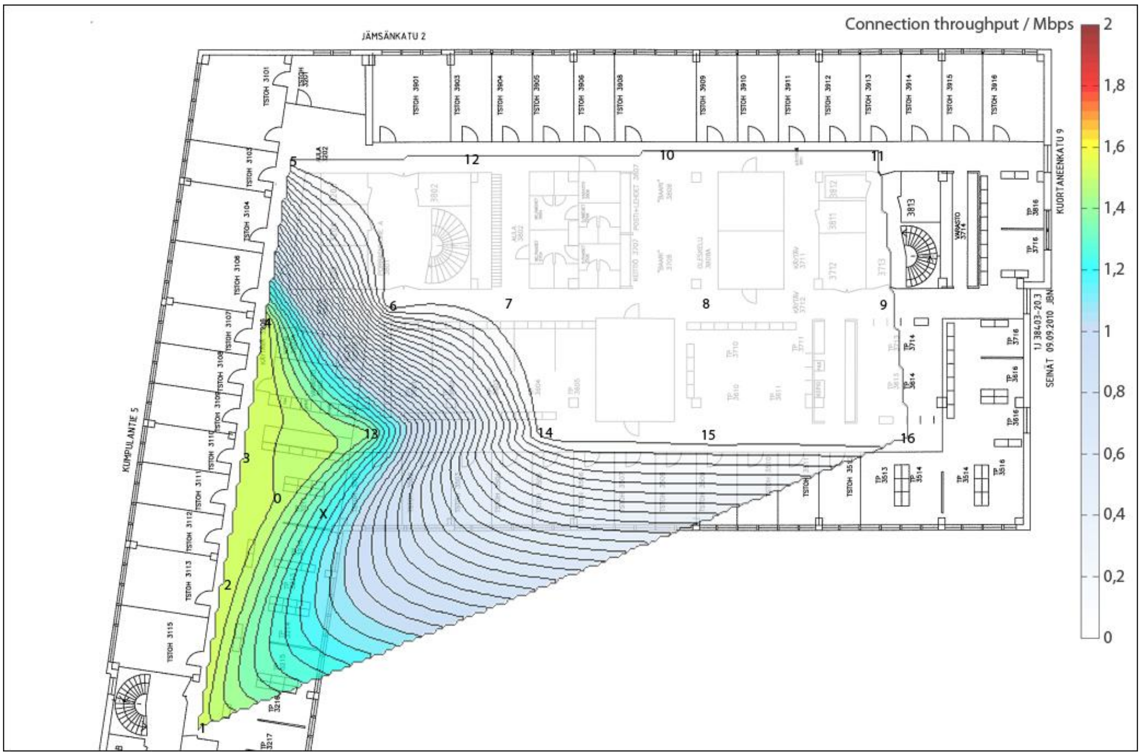

Figure 62. Digita offices 3rd floor WSD downlink throughput.

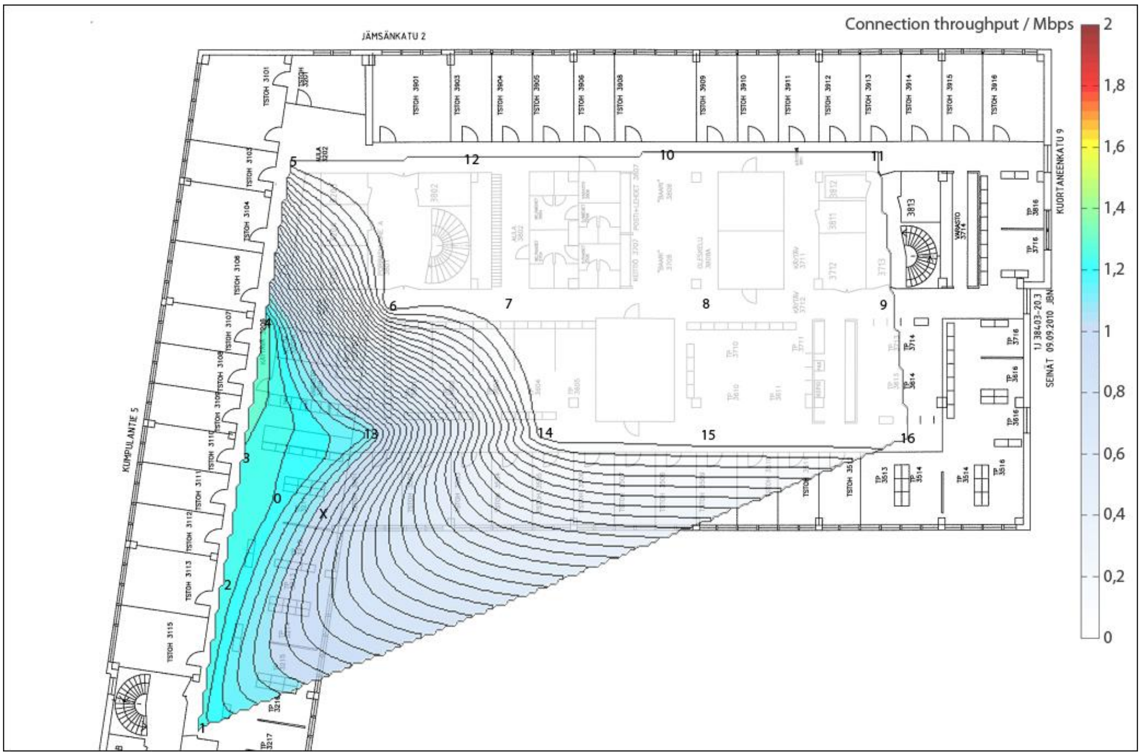

Figure 63. Digita offices 3rd floor WSD uplink throughput.

Both the downlink and uplink throughput coverage are rather stable in the limited area the measurements were possible. Although the WSD connection could be established in more numerous locations, only measurement points 1, 2, 3, 4 and 13 provided good enough connection for the measurement to be possible.

The fifth and final section provides the conclusion to this study.

5 Discussions and Conclusions

The clearest conclusion of the study is that in an area where WLAN access points are abundant in quantity and compete for the same spectrum, white space devices can provide a much better coverage. Even if the area would have several WSD networks, they would not interfere with each other.

There are, however, several difficulties in further analyzing the results. At Nokia research center the WSD reference value was -28,6 dBm and WLAN equivalent -29 dBm. At Digita offices the values were -23,2 dBm and -29,8 dBm respectively. One meter free space path loss for WSD would theoretically be 28,3 dB and for the 2,4 GHz WLAN 40,0 dB. As there was nothing between the transmitters and receivers when carrying out the reference measurements, FSPL would have been the main attenuating factor. The difference between the values from the two buildings is relatively large for the WSD, even keeping in mind the challenges of indoor propagation.

Nevertheless, the equal reference values at NRC would have turned the measurements in favor of the WSD. Based on theoretical figures, the WSD should have had lower attenuation value at the reference point. The WSD measurements at NRC would have had a larger compensation in their attenuation figures than they probably should have had, boosting the relative attenuation difference in favor of the WSD. This however does not remove the fact that in a heavily contested WLAN environment the signal detection was extremely compromised. At Digita the reference values corresponded more to the theoretical calculations, but there still is room for speculation.

Adding more difficulty to the analysis of the Digita measurement results is the fact that the results themselves were compromised due to a design flaw in the measurement software. Approximation of results on 15 dB flat line explained in more detail in the section about wired measurements was far from ideal. Since the values on that flat line were relatively plentiful during the Digita measurements, the problem is further compounded.

In addition to the attenuation figures, also the transmitting power needs to be taken into account. Transmitting powers for WSD and WLAN were 32 dBm and 20 dBm respectively. In theory the reference value for the WSD at one meter range should have been roughly 25 dB higher than for the WLAN. As the transmitters radiate the energy into the surroundings in a roughly similar way, the higher transmitting power should have been evident especially in the reference point. The actual transmitting power of the WSD was confirmed during the wired test measurements to be relatively accurately the nominal 32 dBm. This focuses more attention on the WSD antenna.

For a frequency range around 618 MHz the WSD antenna is far from optimal. The optimal half-wave length of the antenna would have been 24,3 cm but the antenna measured 30,5 cm in length. The WSD kits available from Spectrum Bridge are produced to be used over several frequency ranges, so the antenna is a compromise as it cannot be changed as the frequency changes. From the results it is apparent the antennas of the WSDs are not of good quality or suitable for this particular frequency range.

Another notable aspect is the operating range of the different connection methods. With 32 dBm transmit power and -95 dBm receiver sensitivity the WSD connection could theoretically have handled 127 dB of loss before connection itself is lost. This however was not true due to the evident antenna problems. The real attenuation margin for the WSD connection could only be approximated from the reference measurements, which had somewhat equal values for both connections. Calculation with 20 dBm transmit power and -85 dBm receiver sensitivity for the WLAN gave 105 dB as a maximum possible loss. Based on these figures, the WSD would have had roughly 10 dB larger attenuation margin due to a better receiver sensitivity.

Based on the measurements at Digita, as the measurements at NRC were too compromised, the attenuation for the WSD connection did not clearly show the expected benefits over WLAN. At the ultimate reach of the connections, WSD dominated the WLAN. This however can be attributed to the better sensitivity of the WSD receiver, not the better attenuation behavior of the WSD signal.

Due to a lack of time a proper study on WSD signal attenuation could not be completed. More targeted and specific measurements and analysis of attenuation caused by various types of walls and other obstacles would be required. Based on these measurements a multi-wall model for a WSD connection in this frequency range could be fitted. Also no study on the possible interference of WSD traffic to television broadcasts on the neighboring channels and vice versa could be completed. This would certainly provide an interesting subject for future study.

The benefits of lower frequencies in indoor use remained somewhat unclear based on this study, mainly due to failings in equipment. Even keeping in mind the somewhat inconclusive attenuation conclusions, the benefits of the cognitive radio were apparent. In a heavily contested wireless environment it proved to provide a much better connection than a traditional WLAN.

References

1 Electronic Communications Committee (2011) *ECC Report 159*. Cardiff, IE: ECC.

2 Fette, B. (2006) *Cognitive Radio Technology*. Amsterdam, NL: Elsevier.

3 Akyildiz, I. et al (2006) *Computer Networks 50 - NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey*. Amsterdam, NL: Elsevier.

4 *Experimental White Spaces Network Deployment Kit - Deployment & User Guide*. Lake Mary, US: Spectrum Bridge Inc.

5 Digita (2011) *Digi-tv:n näkyvyysaluekartat (PDF) - digitv.fi* (Feb 21) [WWW document] http://www.digitv.fi/sivu.asp?path=1;8224;4850 (Accessed April 25,.2011)

6 Knight, R.D. (2008) *Physics for Scientists and Engineers – A Strategic Approach*. *2nd edition*. San Francisco, US: Pearson Addison-Wesley.

7 Räisänen, A.V., Lehto, A. (2003) *Radio Engineering for Wireless Communication and Sensor Applications*. Boston, US: Artech House, INC.

8 Anttalainen, T. (2003) *Introduction to Telecommunications Network Engineering*. Boston US: Artech House, INC.

9 Olympus America Inc (2009) *Olympus Microscopy Resource Center: Light and Color – Interference*, (?) [WWW document] http://www.olympusmicro.com/primer/lightandcolor/interference.html (Accessed May 8, 2009)

10 NASA (2007) *Supernovae - Try This!*, (Sep 27) [WWW document] http://imagine.gsfc.nasa.gov/docs/science/try_l2/supernovae.html (Accessed March 6 2009)

11 Aho, O. (2007) *Johtotransmissio - Aaltojohtojen teoria ja sovelluksia.*

12 Mitola, J III (2006) *Cognitive Radio Architecture - The Engineering Foundations of Radio XML*. Hoboken, US: John Wiley & Sons, Inc.

13 Talmola, P. (2002) *DVB-T Radio Network Dimensioning*. Helsinki, FI: Nokia.

14 *Digital Mobile Radio towards Future Generation Systems - COST 231 Final Report*. Brussels, Belgium: COST Telecom Secretariat.

15 *TV White Space Indoor Demo*. Helsinki, FI: Nokia

16 *User Manual - AirStation WHR-G300N.* Austin, US: Buffalo Technology Inc.

17 Institute of Electrical and Electronics Engineers (2007) *IEEE Std 802.11™-2007*. New York, US: IEEE.

18 The SZ development (2011) *Homedale::WLAN Monitor*, (Apr 25) [WWW document] http://thesz.diecru.eu/content/homedale.php (Accessed February 16, 2011)

Test Results

Wired pre-measurements

Attenuator Values (dB)	TVBD Element Manager	Spectrum Analyzer
20+20+0	-14	-14,33
20+20+1	-14	-15,39
20+20+2	-14	-16,35
20+20+3	-15	-17,46
20+20+4	-16	-18,47
20+20+5	-17	-19,31
20+20+6	-17	-20,47
20+20+7	-18	-21,38
20+20+8	-19	-22,43
20+20+9	-20	-23,34
20+20+10	-22	-24,58
20+20+11	-23	-25,56
20+20+12	-24	-26,58
20+20+13	-25	-27,74
20+20+14	-26	-28,68
20+20+15	-27	-29,52
20+20+16	-28	-30,57
20+20+17	-29	-31,58
20+20+18	-30	-32,61
20+20+19	-31	-33,61
20+20+20	-29	-31,44
20+20+21	-30	-32,47
20+20+22	-31	-33,59
20+20+23	-32	-34,73
20+20+24	-33	-35,68
20+20+25	-35	-36,59
20+20+26	-36	-37,58
20+20+27	-37	-38,56
20+20+28	-38	-39,59
20+20+29	-39	-40,65
20+20+30	-41	-41,44
20+20+31	-42	-42,33
20+20+32	-43	-43,38
20+20+33	-44	-44,42
20+20+34	-46	-45,38
20+20+35	-47	-46,16
20+20+36	-48	-47,19
20+20+37	-49	-48,21
20+20+38	-50	-49,17

20+20+39	-51	-50,15
20+20+40	-50	-47,49
20+20+41	-51	-48,46
20+20+42	-53	-49,24
20+20+43	-55	-50,38
20+20+44	-56	-51,37
20+20+45	-57	-52,12
20+20+46	-59	-53,03
20+20+47	-59	-53,94
20+20+48	-60	-54,71
20+20+49	-60	-55,72
20+20+50	-60	-56,56
20+20+51	-60	-57,5
20+20+52	-60	-58,1
20+20+53	-60	-58,87
20+20+54	-60	-59,4
20+20+55	-60	-59,88
20+20+56	-60	-60,38
20+20+57	-59	-60,87
20+20+58	-59	-61,47
20+20+59	-58	-61,89
20+20+60	-60	-59,95
20+20+70	-60	-64,68
20+20+80	-60	-65,88
20+20+80+10	-70	-75,83
20+20+80+20	-77	-75,92

Wired post-measurements

Attenuator Values (dB)	**TVBD Element Manager**
20+20+0+0	-12
20+20+0+1	-13
20+20+0+2	-14
20+20+0+3	-15
20+20+0+4	-16
20+20+0+5	-17
20+20+0+6	-18
20+20+0+7	-19
20+20+0+8	-21
20+20+0+9	-22
20+20+10+0	-23
20+20+10+1	-24
20+20+10+2	-25
20+20+10+3	-26

20+20+10+4	-27
20+20+10+5	-28
20+20+10+6	-30
20+20+10+7	-31
20+20+10+8	-32
20+20+10+9	-33
20+20+20+0	-34
20+20+20+1	-35
20+20+20+2	-36
20+20+20+3	-38
20+20+20+4	-39
20+20+20+5	-40
20+20+20+6	-41
20+20+20+7	-42
20+20+20+8	-43
20+20+20+9	-45
20+20+30+0	-45
20+20+30+1	-47
20+20+30+2	-48
20+20+30+3	-49
20+20+30+4	-50
20+20+30+5	-51
20+20+30+6	-52
20+20+30+7	-53
20+20+30+8	-54
20+20+30+9	-55
20+20+40+0	-56
20+20+40+1	-57
20+20+40+2	-58
20+20+40+3	-59
20+20+40+4	-59
20+20+40+5	-60
20+20+40+6	-60
20+20+40+7	-60
20+20+40+8	-60
20+20+40+9	-60
20+20+50+0	-60
20+20+50+1	-60
20+20+50+2	-60
20+20+50+3	-60
20+20+50+4	-60
20+20+50+5	-60
20+20+50+6	-60
20+20+50+7	-60

20+20+50+8	-60
20+20+50+9	-60
20+20+60+0	-60
20+20+60+1	-61
20+20+60+2	-62
20+20+60+3	-63
20+20+60+4	-64
20+20+60+5	-65
20+20+60+6	-66
20+20+60+7	-67
20+20+60+8	-68
20+20+60+9	-69
20+20+70+0	-69
20+20+70+1	-70
20+20+70+2	-71
20+20+70+3	-72
20+20+70+4	-73
20+20+70+5	-74
20+20+70+6	-75
20+20+70+7	-76
20+20+70+8	-77
20+20+70+9	-79
20+20+70+10	-79
20+20+70+11	-80
20+20+70+12	-81
20+20+70+13	-82

Wireless measurements

	WSD							**WLAN**				
#	**no1**	**no2**	**no3**	**no4**	**no5**	**DL**	**UL**	**no1**	**no2**	**no3**	**no4**	**no5**
1	-36	-33	-37	-36	-36	1,67	1,48	-37	-34	-32	-36	-36
2	-54	-43	-42	-48	-50	1,69	1,54	-41	-44	-46	-38	-43
3	-38	-43	-45	-45	-34	1,68	1,65	-42	-42	-38	-36	-41
4	-56	-56	-56	-54	-53	1,68	1,57	-48	-56	-48	-52	-47
5	-60	-60	-60	-54	-55	1,69	1,66	-58	-56	-49	-63	-49
6	-58	-58	-58	-60	-60	1,68	1,61	-69	-61	-65	-61	-62
7	-69	-70	-69	-72	-72	-	-	-	-	-	-	-
8	-63	-68	-61	-70	-60	1,67	1,55	-	-	-	-	-

Measurement Results - Nokia Research Center

Fourth floor

	WSD					WLAN				
#	no1	no2	no3	no4	no5	no1	no2	no3	no4	no5
1	-28	-38	-29	-21	-27	-27	-31	-30	-28	-29
2	-34	-28	-31	-29	-34	-34	-36	-33	-37	-34
3	-38	-42	-31	-41	-42	-37	-38	-33	-32	-39
4	-50	-44	-45	-44	-50	-43	-51	-44	-48	-51
5	-40	-35	-46	-43	-45	-43	-46	-50	-42	-47
6	-46	-28	-35	-35	-34	-36	-36	-41	-38	-37
7	-52	-55	-53	-58	-50	-54	-55	-56	-61	-59
8	-44	-57	-52	-44	-51	-53	-58	-52	-56	-53
9	-46	-50	-59	-48	-53	-57	-53	-57	-54	-58
10	-65	-54	-50	-59	-58	-	-	-	-	-
11	-71	-65	-65	-72	-74	-	-	-	-	-
12	-62	-65	-64	-61	-56	-	-	-	-	-
13	-61	-63	-70	-62	-70	-70	-	-	-	-
14	-69	-69	-66	-61	-58	-	-	-	-	-
15	-78	-	-	-	-	-	-	-	-	-
16	-78	-78	-78	-74	-77	-	-	-	-	-
17	-58	-55	-68	-63	-57	-	-	-	-	-
18	-52	-55	-64	-62	-	-	-	-	-	-
19	-58	-50	-54	-59	-49	-66	-	-	-	-
20	-79	-76	-	-70	-65	-	-	-	-	-
21	-66	-70	-68	-65	-	-	-	-	-	-
22	-70	-80	-77	-70	-76	-	-	-	-	-
23	-64	-65	-69	-64	-62	-74	-70	-76	-73	-
24	-69	-63	-65	-67	-78	-	-	-	-	-
25	-75	-71	-69	-72	-75	-	-	-	-	-
26	-70	-69	-60	-68	-65	-76	-79	-79	-	-
27	-58	-57	-56	-55	-53	-68	-63	-72	-66	-69
28	-70	-78	-79	-64	-64	-69	-74	-67	-	-
29	-67	-69	-62	-66	-65	-	-	-	-	-
30	-60	-61	-69	-66	-61	-	-	-	-	-
31	-61	-67	-58	-59	-60	-	-	-	-	-
32	-65	-61	-57	-63	-66	-	-	-	-	-
33	-51	-55	-56	-57	-51	-	-	-	-	-
34	-50	-49	-51	-48	-53	-	-	-	-	-
35	-60	-57	-46	-54	-55	-	-	-	-	-
36	-50	-57	-54	-54	-47	-60	-62	-59	-61	-64
37	-60	-62	-58	-57	-53	-68	-	-	-	-
38	-67	-61	-63	-65	-62	-70	-74	-74	-	-

39	-66	-65	-69	-62	-61	-	-	-73	-71	-75
40	-66	-71	-70	-69	-70	-79	-	-	-	-
41	-	-	-	-	-	-	-	-	-	-
42	-	-	-	-	-	-	-	-	-	-
43	-	-	-	-	-	-	-	-	-	-
44	-	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-
46	-69	-72	-74	-78	-81	-	-77	-	-81	-75
47	-80	-84	-	-	-	-	-	-	-	-

Third floor

	WSD					WLAN				
#	**no1**	**no2**	**no3**	**no4**	**no5**	**no1**	**no2**	**no3**	**no4**	**no5**
1	-56	-68	-63	-75	-65	-77	-	-	-	-
2	-53	-56	-60	-59	-66	-	-	-	-	-
3	-61	-60	-58	-62	-66	-68	-	-	-	-
4	-54	-54	-60	-63	-57	-65	-	-	-	-
5	-63	-61	-71	-71	-67	-80	-	-	-	-
6	-66	-72	-62	-63	-62	-	-	-	-	-
7	-66	-71	-75	-70	-69	-80	-	-	-	-
8	-69	-68	-63	-66	-66	-75	-	-	-	-
9	-79	-70	-76	-74	-75	-	-	-	-	-
10	-75	-76	-68	-70	-76	-	-	-	-	-
11	-77	-62	-69	-74	-	-	-	-	-	-
12	-71	-73	-76	-80	-82	-	-	-	-	-
13	-76	-66	-75	-62	-72	-59	-74	-75	-	-
14	-57	-70	-62	-63	-62	-	-	-	-	-
15	-59	-63	-67	-70	-68	-	-	-	-	-

Second floor

	WSD					WLAN				
#	**no1**	**no2**	**no3**	**no4**	**no5**	**no1**	**no2**	**no3**	**no4**	**no5**
1	-56	-67	-66	-56	-59	-	-	-	-	-
2	-75	-82	-76	-74	-70	-	-	-	-	-
3	-74	-	-76	-85	-	-	-	-	-	-
4	-69	-67	-68	-69	-70	-	-	-	-	-
5	-56	-68	-64	-61	-68	-	-	-	-	-
6	-70	-	-66	-69	-73	-	-	-	-	-
7	-74	-81	-82	-87	-74	-	-	-	-	-
8	-66	-74	-71	-71	-71	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-
10	-73	-72	-71	-75	-73	-	-	-	-	-
11	-60	-60	-66	-61	-61	-64	-	-	-	-64

12	-65	-65	-56	-59	-63	-	-	-	-71	-66
13	-68	-59	-57	-55	-64	-73	-	-	-68	-
14	-68	-80	-69	-69	-70	-	-	-79	-	-

First floor

	WSD					WLAN				
#	**no1**	**no2**	**no3**	**no4**	**no5**	**no1**	**no2**	**no3**	**no4**	**no5**
1	-64	-61	-66	-63	-69	-	-	-	-	-
2	-74	-76	-69	-72	-76	-	-	-	-	-
3	-	-74	-72	-76	-73	-	-	-	-	-
4	-71	-78	-71	-79	-71	-	-	-	-	-
5	-73	-82	-81	-79	-76	-	-	-	-	-
6	-72	-68	-76	-72	-68	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-
8	-64	-66	-67	-68	-71	-	-	-	-	-
9	-66	-64	-62	-68	-68	-	-	-	-	-
10	-65	-61	-61	-72	-61	-	-	-	-	-
11	-61	-72	-68	-73	-62	-	-	-	-	-
12	-55	-67	-63	-63	-70	-	-	-	-61	-63
13	-58	-62	-55	-49	-56	-	-	-	-	-61
14	-71	-65	-68	-75	-73	-	-	-	-	-79

Measurement Results - Digita

Sixth floor

	WSD							WLAN				
#	no1	no2	no3	no4	no5	DL	UL	no1	no2	no3	no4	no5
1	-31	-22	-23	-18	-22	1,71	1,61	-35	-28	-26	-29	-31
2	-37	-31	-35	-33	-24	1,69	1,63	-32	-33	-34	-31	-32
3	-26	-24	-26	-21	-34	1,72	1,57	-34	-42	-37	-33	-39
4	-24	-19	-25	-31	-35	1,71	1,56	-42	-45	-37	-39	-38
5	-41	-30	-35	-32	-47	1,68	1,54	-44	-45	-44	-42	-41
6	-47	-46	-53	-53	-44	1,69	1,65	-50	-44	-51	-48	-44
7	-46	-50	-43	-39	-38	1,78	1,55	-57	-56	-57	-61	-59
8	-17	-25	-19	-38	-21	1,71	1,49	-33	-36	-34	-35	-34
9	-37	-39	-33	-27	-25	1,74	1,61	-43	-47	-42	-39	-42
10	-60	-35	-44	-52	-38	1,75	1,65	-53	-45	-48	-49	-48
11	-53	-43	-48	-45	-44	1,71	1,64	-56	-55	-53	-54	-53
12	-45	-57	-45	-57	-51	1,7	1,56	-58	-62	-55	-55	-59
13	-49	-51	-54	-59	-52	1,67	1,56	-66	-58	-59	-59	-59
14	-55	-56	-53	-49	-49	1,69	1,49	-67	-61	-62	-57	-60
15	-60	-60	-60	-60	-60	1,69	1,53	-71	-73	-79	-73	-79
16	-60	-60	-60	-60	-62	1,72	1,66	-83	-84	-83	-81	-78
17	-60	-60	-63	-60	-60	1,74	1,57	-81	-80	-81	-79	-79
18	-75	-70	-67	-75	-74	1,37	1,25	-81	-	-	-	-
19	-64	-67	-62	-63	-71	1,67	1,56	-	-81	-	-	-82
20	-81	-61	-64	-69	-67	1,68	1,66	-	-	-	-	-
21	-63	-64	-73	-66	-62	1,7	1,58	-	-	-	-	-
22	-71	-71	-77	-67	-74	-	-	-	-	-	-	-
23	-77	-84	-	-86	-	-	-	-	-	-	-	-
24	-86	-80	-84	-86	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-	-	-	-
28	-76	-71	-64	-72	-64	1,61	1,57	-78	-81	-77	-79	-79
29	-68	-69	-76	-69	-66	1,67	1,61	-78	-81	-	-80	-81
30	-76	-64	-69	-70	-60	1,77	1,56	-79	-76	-77	-78	-77
31	-64	-67	-69	-67	-61	1,89	1,61	-	-	-	-	-
32	-58	-61	-62	-58	-60	1,68	1,54	-74	-76	-75	-73	-78
33	-62	-67	-60	-64	-61	1,74	1,56	-77	-77	-	-	-81
34	-65	-68	-60	-60	-64	1,7	1,6	-74	-	-	-80	-84
35	-58	-62	-59	-61	-59	1,66	1,62	-77	-73	-72	-74	-75
36	-67	-60	-69	-60	-60	1,68	1,55	-77	-74	-71	-74	-79
37	-63	-60	-61	-69	-60	1,68	1,51	-80	-79	-78	-74	-79
38	-61	-58	-59	-59	-60	1,69	1,55	-72	-67	-71	-71	-74

39	-55	-56	-61	-58	-57	1,69	1,55	-68	-69	-69	-70	-69
40	-60	-61	-59	-56	-59	1,7	1,45	-75	-74	-72	-73	-69
41	-62	-63	-67	-60	-60	1,95	1,49	-79	-76	-78	-72	-77
42	-58	-64	-62	-60	-6	1,72	1,6	-71	-69	-72	-69	-72
43	-60	-61	-58	-57	-57	1,74	1,14	-70	-73	-69	-65	-63
44	-60	-60	-60	-60	-60	1,76	0,72	-83	-81	-80	-77	-79
45	-50	-54	-52	-43	-58	1,69	1,45	-62	-63	-65	-61	-64

Fifth floor

	WSD							**WLAN**				
#	**no1**	**no2**	**no3**	**no4**	**no5**	**DL**	**UL**	**no1**	**no2**	**no3**	**no4**	**no5**
1	-56	-58	-59	-56	-52	1,66	1,57	-64	-63	-58	-64	-62
2	-51	-54	-47	-57	-48	1,69	1,56	-67	-55	-64	-66	-62
3	-49	-51	-48	-48	-49	1,71	1,53	-50	-53	-54	-53	-50
4	-59	-58	-54	-53	-57	1,68	1,57	-68	-62	-66	-60	-65
5	-60	-60	-64	-60	-60	1,59	1,34	-77	-72	-77	-77	-81
6	-62	-68	-64	-63	-64	1,58	0,15	-	-	-	-82	-80
7	-65	-73	-67	-61	-62	1,63	0,19	-82	-84	-82	-80	-81
8	-69	-66	-71	-66	-70	1,56	1,39	-	-	-	-	-84
9	-68	-66	-73	-69	-70	1,56	1,28	-	-	-	-	-
10	-80	-74	-78	-80	-75	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-
12	-65	-71	-75	-73	-67	1,53	1,17	-	-	-	-81	-82
13	-69	-71	-68	-65	-62	1,57	1,29	-79	-	-	-	-
14	-62	-67	-64	-67	-72	1,59	1,2	-77	-80	-	-82	-80
15	-60	-60	-60	-60	-60	1,55	1,31	-71	-78	-75	-76	-78
16	-64	-62	-66	-60	-61	1,61	1,26	-79	-80	-81	-78	-75
17	-62	-60	-60	-60	-60	1,57	1,26	-83	-77	-76	-77	-81
18	-60	-60	-60	-58	-60	1,55	1,34	-71	-80	-76	-70	-79

Third floor

	WSD							**WLAN**				
#	**no1**	**no2**	**no3**	**no4**	**no5**	**DL**	**UL**	**no1**	**no2**	**no3**	**no4**	**no5**
1	-67	-61	-65	-68	-68	1,57	1,27	-	-	-	-	-80
2	-66	-73	-71	-69	-63	1,57	1,27	-	-	-	-	-
3	-63	-62	-64	-62	-60	1,55	1,28	-	-	-	-	-83
4	-62	-66	-78	-73	-71	1,58	1,33	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-
6	-80	-70	-76	-72	-79	-	-	-	-	-	-	-
7	-74	-84	-75	-74	-81	-	-	-	-	-	-	-
8	-86	-88	-84	-81	-78	-	-	-	-	-	-	-
9	-84	-83	-82	-88	-80	-	-	-	-	-	-	-
10	-77	-79	-77	-80	-78	-	-	-	-	-	-	-

11	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-
13	-61	-65	-74	-70	-65	1,45	1,16	-	-	-	-	-
14	-75	-71	-77	-72	-79	-	-	-	-	-	-	-